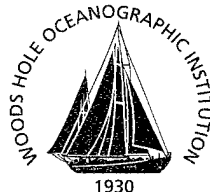
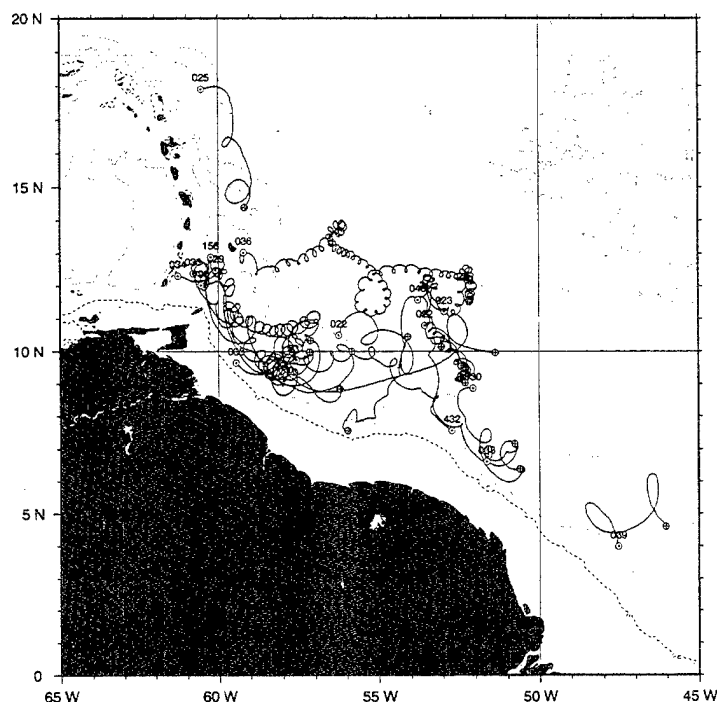


# Woods Hole Oceanographic Institution

Woods Hole, MA 02543



## North Brazil Current Rings Experiment: RAFOS Float Data Report: November 1998 – June 2000



by

Christine M. Wooding, Philip L. Richardson, Marguerite A. Pacheco  
Deborah A. Glickson, and David M. Fratantoni

July 2002

### Technical Report

Funding was provided by the National Science Foundation under Grant No. OCE-9729765 and OCE-0136477.

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**Approved for Distribution:**



Nelson G. Hogg, Chair

Department of Physical Oceanography

## **Abstract**

Twenty-one RAFOS floats were tracked at depths of 200-1000 meters in and around several North Brazil Current Rings between November 1998 and June 2000. This was part of an experiment to study the role of these current rings in transporting upper level South Atlantic water across the equatorial-tropical gyre boundary into the North Atlantic subtropical gyre. The float trajectories in combination with surface drifters and satellite imagery reveal the sometimes complex life histories of several rings and their fate as they collide with the Lesser Antilles Islands. This report describes the float trajectories, the velocity, temperature, and depth time series, and a preliminary analysis of the float data.

**Front Cover Figure Caption:** Trajectories of floats that completed at least two loops in the same direction. Seventeen loopers are superposed here. A small cross marks the beginning and a small dot the end of each looper. The loopers are interpreted to be measurements of discrete eddies; the clockwise loopers are NBC rings.

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## 1. Introduction

North Brazil Current (NBC) rings are large (400 km diameter) anticyclones that pinch off from the NBC retroflection in the western tropical Atlantic near 8N and translate northwestward along the coast of South America toward the Caribbean (Johns *et al.*, 1990; Didden and Schott, 1993; Richardson *et al.*, 1994; Fratantoni *et al.*, 1995). NBC rings have been proposed as one of several important mechanisms for the transport of South Atlantic upper-ocean water across the equatorial-tropical gyre boundary and into the North Atlantic subtropical gyre. Such transport is required to complete the meridional overturning cell in the Atlantic forced by the high-latitude production and southward export of North Atlantic Deep Water. The mechanisms that contribute to NBC ring formation and the structure and dynamics of the rings themselves are not well understood. The purpose of this study is to obtain, for the first time, comprehensive observations of the NBC retroflection, the NBC ring formation process, and the physical structure and properties of NBC rings as they translate northwestward along the low-latitude western boundary. The goal is to understand the process of NBC ring generation and to quantify the role of NBC rings in cross-equatorial and cross-gyre transport within the Atlantic meridional overturning cell. Specific objectives of the float component of the NBC Rings Experiment are to:

1. Measure and describe the physical structure of NBC rings after separation from the NBC, including both near-synoptic and time-evolving temperature and velocity characteristics.
2. Determine characteristic rates of translation, mixing, and decay as NBC rings move northwestward toward the Caribbean Sea.
3. Identify the long-term fate of South Atlantic water trapped within the ring core, and determine the effective intergyre ring transport in several temperature/density watermass classes.

## 2. Float Deployment

Four cruises were conducted during the North Brazil Current Rings Experiment. On each cruise, shipboard ADCP, XBT, and CTD-LADCP surveys were used to locate NBC rings and to measure their physical properties (Fleurant *et al.*, 2000a, b, c). Subsurface floats were deployed during the first three cruises (see Table 1) and during a non-NBC cruise following cruise 2. Two acoustic sound sources (S1 and S2) were deployed on the first cruise and retrieved on the fourth. An ALFOS float was also launched on the first cruise in order to monitor the sources.

**Table 1. Number of RAFOS floats launched during each cruise.**

Cruise	Beginning Date	Ending Date	RAFOS Floats Launched	
			Total	Into Rings
NBC 1	11-07-98	12-11-98	14	13
NBC 2	02-06-99	03-09-99	11	9
NBC 3	01-29-00	02-24-00	2	2
NBC 4	07-06-00	23-06-00	0	0

Note: All cruises were on the *R/V Seward Johnson*.

The floats equilibrated, on average, deeper than their target depths. We have divided them into three main depths: a shallow layer near 250 m, a mid-depth layer near 550 m, and a deep layer near 900 m. North Atlantic Deep Water (NADW) is located below roughly 1000 m; it flows southward on average, counter to the translation direction of the rings. The swirl velocity of several rings extended into the NADW, but because one of the goals of the NBC Ring Experiment was to measure the northward flux of South Atlantic Water, the floats were confined to depths less than 1000 m.



### 3. Description of the Floats

The North Brazil Current Rings Experiment used three different kinds of subsurface floats. One was an ALFOS (ALACE-RAFOS) float, which surfaced once every 10 days and transmitted like a very short-mission RAFOS float. There were six RAFOS floats of the "standard ROM" type, and there were 22 of the latest kind of RAFOS float, the DLD2 (see Appendix A for a discussion of DLD2 technology).

Eighteen DLD2 floats were purchased from Seascan Corporation of Falmouth, Mass., and assembled, calibrated (temperature and pressure), and ballasted at WHOI. Four other DLD2 floats, prototypes provided earlier by Seascan that had been used for testing in the WHOI float laboratory, were also used. Six additional floats were assembled from spare parts and parts of floats retrieved from earlier experiments. The ALFOS float, assembled at WHOI, was used to monitor the sound sources.

The floats recorded temperature, pressure, and times of arrival (TOAs) of sound signals transmitted by moored sound sources. At the end of their missions, the floats dropped ballast weights, rose to the ocean surface and transmitted data to WHOI via the Service Argos Inc. satellite system.

Four of the 22 DLD2 floats were never heard by Service Argos, and one (float 037) was not tracked because it went deeper than its depth limit and surfaced after only 36 hours. Two of the six older-design floats were not tracked because of poor-quality TOAs. Overall we obtained 21 trajectories, although some were shorter than planned (Figure 1). Considering that we purchased 18 floats, this seems like a good record.

The majority of floats was deployed on two cruises roughly two months apart. In order to have most of the floats complete their missions in the same time period, the later-deployed floats were scheduled for shorter missions than the earlier ones. The DLD2 floats were set to repeat their listening schedule every 12 hours. Two of the standard-ROM RAFOS floats were also set to repeat listening every 12 hours; the other four repeated every 24 hours.

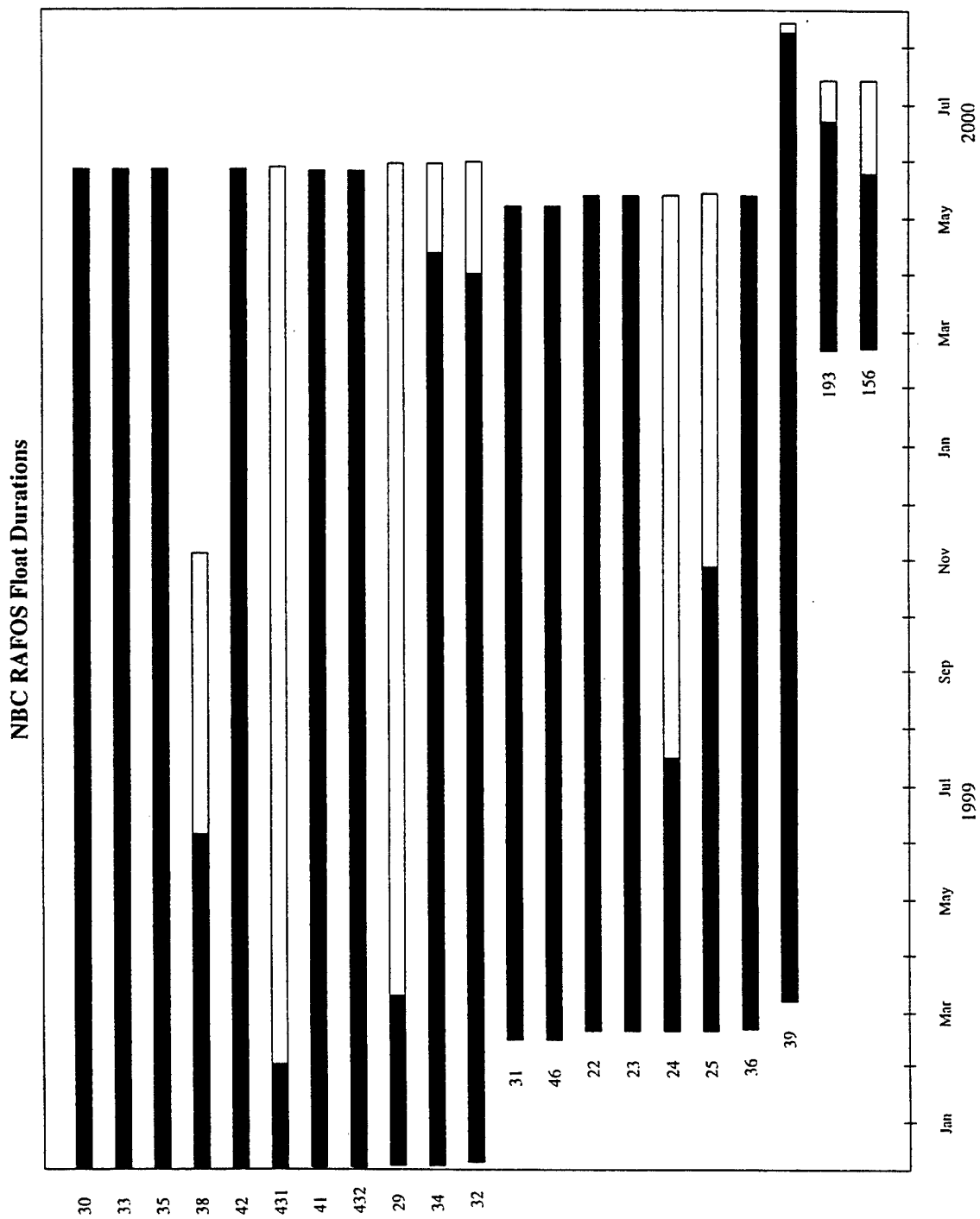


Figure 1. Float duration chart. Float numbers are shown to the left of the line that indicates submerged time. The dark part of the line indicates when the float was tracked. Floats are listed in order of launch date.

The floats were generally set to listen starting at 0100, 0130, and 0200. Nothing was gained by including the 0200 window, and little was lost by omitting the 0030 window. However, the tracking program is hard-wired for 0030, 0100, 0130, and for 17 columns per record. This meant that an extra step was needed, splitting the longer records, and shifting all TOAs and correlations right four columns, inserting a "null" 0030 window.

Columns before conversion:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
count	0100		0130						0200							T&P

Columns after conversion:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
count	0030		0100		0130											T&P
	(null)															

Neither kind of RAFOS float stored the complete temperature or pressure values. This means that a target value must be assigned, and the appropriate rollover value applied until the result is within range of the target. The DLD2s used the last-recorded pressure and temperature of the mission as a default target (for earlier floats, the target was assigned). These values were often at the maximum or minimum. The floats also experienced a wide range of temperatures (especially those reaching the Caribbean or going ashore). For these reasons, a number of floats (18 of 21) needed second and sometimes third targets to get the pressure and temperature correct, before they could be processed.

The floats were ballasted to drift at a preset depth. This involved weighing the floats in air and in water at different pressures (see Tables 2 and 3). Two floats (037 and 038) surfaced early due to exceeding their pressure limits. On average the floats equilibrated 73 m deeper than their ballast depths. RAFOS floats 431 and 432 were always shallower by 25 to 75 m than their target depths. Floats 156 and 193 had mean pressures close to their targets. The DLD2s were all deeper than their target depths throughout their missions.

**Table 2. RAFOS float summary – launch and end positions**

Float	Launch			Surface			Target	Equil	Mean	Mean		
	Date	Lat	Lon	Date	Lat	Lon	Depth	Depth	Temp	Depth	Ring	CTD
	yymmdd	° N	° W	yymmdd	° N	° W	m.	m.	° C.	m.		
<b>DLD2 Floats</b>												
022	990219	9.179	52.439	000513	12.633	52.287	450	550	7.38	530	R3	2-42
023	990219	9.179	52.439	000513	7.981	47.296	800	910	5.21	907	R3	2-42
024	990219	8.780	52.481	000513	13.063	74.758	200	250	11.90	268	R3	2-41
025	990219	9.179	52.439	000513	15.086	70.016	200	250	13.90	282	R3	2-42
029	981208	8.841	56.242	000530	10.018	77.339	200	275	11.70	269	R1	
030	981206	6.405	50.521	000527	8.756	48.164	450	555	7.44	531	R2	1-52
031	990213	10.266	57.203	000507	16.681	52.500	450	540	8.34	512	R2	2-23
032	981209	9.218	56.373	000531	19.544	66.109	450	620	7.29	592	R1	1-64
033	981206	6.405	50.521	000527	12.544	58.603	200	320	10.24	311	R2	1-52
034	981208	8.841	56.242	000530	13.571	64.200	450	600	7.38	527	R1	
035	981206	7.112	50.771	000527	12.177	60.228	450	540	7.56	502	R2	1-53
036	990219	8.780	52.481	000513	12.209	52.102	800	860	5.31	843	R3	2-41
037	990302	5.498	48.321	990304	5.298	48.366	800	1000	Not tracked		R4	2-68
038	981206	7.112	50.771	991104	1.685	23.879	200	240	15.03	248	R2	1-53
039	990305	2.671	47.336	000814	1.367	35.457	800	880	4.87	879	NBC	2-80
040	981208	8.841	56.242				800		Never heard		R1	
041	981206	7.112	50.771	000527	6.782	46.751	800	890	4.98	860	R2	1-53
042	981206	6.405	50.521	000527	12.881	50.788	800	870	5.22	860	R2	1-52
043	990411	8.314	52.608				200		Never heard		NBC	
044	990219	8.780	52.482				450		Never heard		R3	2-41
045	990213	10.266	57.203				200		Never heard		R2	2-23
046	990213	10.266	57.203	000507	9.547	55.230	800	840	5.36	891	R2	2-23
<b>Older-design RAFOS Floats</b>												
156	000220	10.020	57.103	000714	13.779	63.230	200	220	12.95	223	R5	3-52
193	000220	10.020	57.103	000714	14.478	61.948	450	520	9.79	491	R5	3-52
430	981209	8.901	56.177	000607	9.936	84.087	200		Not tracked		R1	1-63
431	981205	6.231	49.509	000528	4.795	1.957	200	180	18.65	148	R2	1-50
432	981206	7.112	50.771	000528	11.110	49.987	1000	950	4.98	935	R2	1-53
433	981209	9.218	56.373	000227	14.360	68.639	200		Not tracked		R1	1-64

Floats 022 - 046 were DLD2 floats that listened and recorded T/P every 12 hours. Float 43 was deployed by John Whitehead from *R/V Oceanus*. Floats 156 and 193 were older, re-powered RAFOS floats that listened every 12 hours and recorded T/P every 24. Floats 430 - 433 were older-design RAFOS floats that listened and recorded T/P every 24 hours. R1 refers to Ring 1, *etc.* These designations are internal to this report. The station number in the last column denotes the cruise and the CTD taken at the time that float was launched (Fleurant *et al.*, 2000a, b, c).

**Table 3. RAFOS float summary – performance**

	Startup	Expected	Actual	Offsets (secs)		Messages		Track-able	Sources	Comments
Float	Date	Surface	Surface	Initial	Final	Received	%	Months	Heard	
037	990221	000814	990304			2/2		0/0		surfaced after 36 hrs
038	981204	000527	991104	0.0	0.23	329/334	98	6/11	4	out-of-range to east
045	990213	000508								never heard
031	990213	000508	000507	0.0	0.68	450/450	100	15/15	5	
046	990213	000508	000507	0.0	-2.02	450/450	100	15/15	6	"exponential" pressure
024	990218	000513	000514	-1.0	1.19	432/450	96	5/15	3	ended in Caribbean
025	990218	000513	000514	-1.0	1.45	446/450	99	9/15	4	ended in Caribbean
022	990218	000513	000514	-1.0	1.58	445/450	99	15/15	5	
044	990218	000513								never heard
023	990218	000513	000514	-2.0	2.76	440/450	97	15/15	5	
036	990218	000513	000514	-1.0	1.55	341/540	63	15/15	6	
030	981204	000527	000527	0.0	2.07	537/540	99	18/18	5	
033	981204	000527	000527	0.0	0.86	539/540	99	18/18	4	
035	981204	000527	000527	0.0	2.00	540/540	100	18/18	6	
041	981204	000527	000527	0.0	4.04	481/540	89	18/18	5	
042	981204	000527	000527	0.0	3.76	539/540	99	18/18	6	
431	981205	000528	000528	-23.0	-206.4**	215/271	79	2/18	2	*TOAs end at surface
432	981205	000528	000528	-24.0	-258.0	246/271	91	18/18	5	
029	981208	000531	000530	0.0	2.67	538/540	99	3/18	2	ended in Caribbean
034	981208	000531	000530	0.0	-0.32	538/540	99	16/18	6	ended in Caribbean
040	981208	000531								never heard
032	981209	000601	000531	0.0	3.30	466/540	86	15/18	4	ended in Caribbean
433	981209	000601	000227	-24.0	-194.8	212/223	95	0/18	2	battery failure?
430	981209	000602	000601	-22.0	-158.5	67/271	25	0/18	0	*on surface, no TOAs
043	990409	000702								never heard
156	000215	000714	000714	4.0	0.19	151/151	100	3/5	4	ended in Caribbean
193	000215	000714	000714	2.0	-6.77	150/151	99	4/5	4	ended in Caribbean
039	990221	000814	000814	0.0	1.22	441/540	82	18/18	6	

All dates are year-month-day.

\* The first Argos transmissions for these two floats were on land.

\*\* The final offset for 431 was reduced to -67.31 to match the TOA end date of 990414.

One advantage of RAFOS floats over the previous SOFAR floats is that two end points are available to check the acoustic tracking: the launch location and the surfacing location, obtained from Service Argos' calculation of the locus of the transmitter. The surfacing location was not useful in two cases because the floats were on land before they began transmitting. Float 430 stayed submerged for 100 days; it was probably picked up around day 250. Float 430 first transmitted from Costa Rica. Float 431 stayed submerged for 120 days, and was picked up after 200 days. It first transmitted from Point Three Points in Ghana (so-called because it is the land closest to the Equator, the Greenwich Meridian and sea-level).

Before we received all messages from 432, it was picked up and taken to Martinique. From there it was returned to Woods Hole.

Five floats (029, 031, 032, 034, 046) shared identical zeroeth messages (roughly one-half of their first output records). This had the effect of making them look like they had recorded 450 messages in 449 days. In order to produce the correct result, the start dates had to be moved one day earlier than shown in the launch logs. It is not clear why these floats failed to overwrite the default information in the zeroeth message.

Several floats (see 031, 033, and 035) show a clumping or quantizing in their temperature records. This is a result of being located in layers of nearly constant temperature and salinity (Schmitt *et al.*, 1987)

Float 433 had no useable TOAs after 80 records, and only heard one source. It stopped collecting data and began transmitting after 223 days and gave its final status as "on the surface." The TOA record is typical of the case where the battery voltage drops.

RAFOS floats can detect when they are on the surface by recrossing a minimum pressure and also exceeding a maximum temperature. Because of past problems, for the NBC experiment the minimum pressure was set to 1000 counts, very close to (and sometimes above) the surface. This explains why 430 and 431 continued "in mission" after reaching the surface, and suggests that the "on surface" status of 433 was caused by low voltage.

The pressure record of float 046 repeatedly sweeps the same 150-meter range. No oceanographic explanation has been posited and these results are attributed to instrument problems.

The DLD2 floats can store message-numbers up to 2048, but the earlier floats can only store values up to 256. The checksum is used to decide whether a message-number is greater than 256 or not. This creates uncertainty when you want to fill in gaps in the received data with messages with bad checksums. This was an issue for floats 431 and 432.

#### 4. Description of Sound Sources

The NBC floats used sources deployed by scientists from three different countries for five different experiments (Table 4, Figures 2, 3). The oldest source used, 185, was deployed October 19, 1994, as part of the Deep Western Boundary Current Experiment (BOUNCE) (Hunt and Bower, 1998). Source 185's clock had drifted at a faster rate than was deduced at the end of BOUNCE, so an expedient offset was applied the one time it was used.

**Table 4: Sound source summary**

	ID	Pong	Corr	Rep	Start	End	Offset	Drift	Depth	Lat	Lon	S.V.
Exp.		Time	(min)	Rate	Date	Date	(sec)	(sec/rep)	(m)	° N	° W	(m/sec)
BOUNCE	185	0100	0	12	941019	none	0.561	0.0057	1500	36.687	58.263	1484
French	B1	0100	0	24	950101	none	0.0	0.005	1000	7.028	49.925	1480
DBE	191	0100	0	24	950212	none	0.0	0.0	1000	-0.327	32.643	1482
NBC	69	0100	0	12	981108	000622	0.0	0.0043	650	13.000	57.886	1484
NBC	77	0130	-30	12	981110	000620	0.0	0.0113	700	12.996	51.107	1484
MOVE	403	0035	25	24	000117	none	0.0	0.0	1100	21.938	62.570	1484
MOVE	404	0100	0	24	000129	010103	-3.0	0.0	1110	15.324	51.526	1484
MOVE	406	0130	-30	24	000204	001230	0.0	0.0	1088	16.333	60.499	1484

The column labeled "corr (min)" refers to the number of minutes that times of arrival for that source were shifted by interpolation to make all sources simultaneous before the resulting location was calculated. "Rep rate" is the time in hours between sound transmissions ("pongs"). The "offset" is the amount the source clock was slow in seconds at launch. The "drift" is the change in the source clock in seconds for each pong (negative means fast). "S.V." indicates sound velocity.

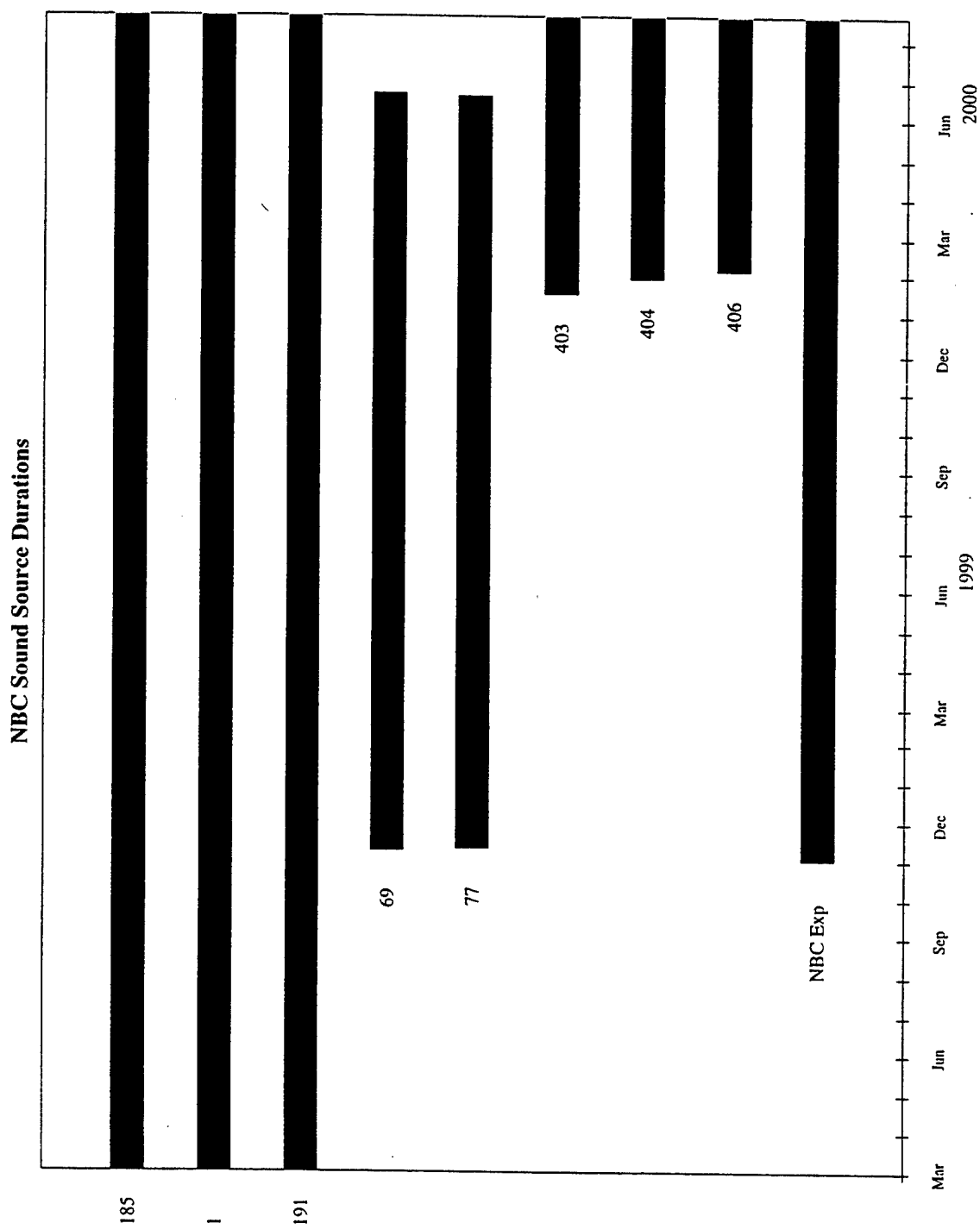


Figure 2. Sound source durations ordered by deployment date. ID numbers are shown to the left of the line. Contact with the plot edge indicates that the start or end is off the plot, except for the last line that represents the duration of this experiment.



## NBC RAFOS Float Sound Sources

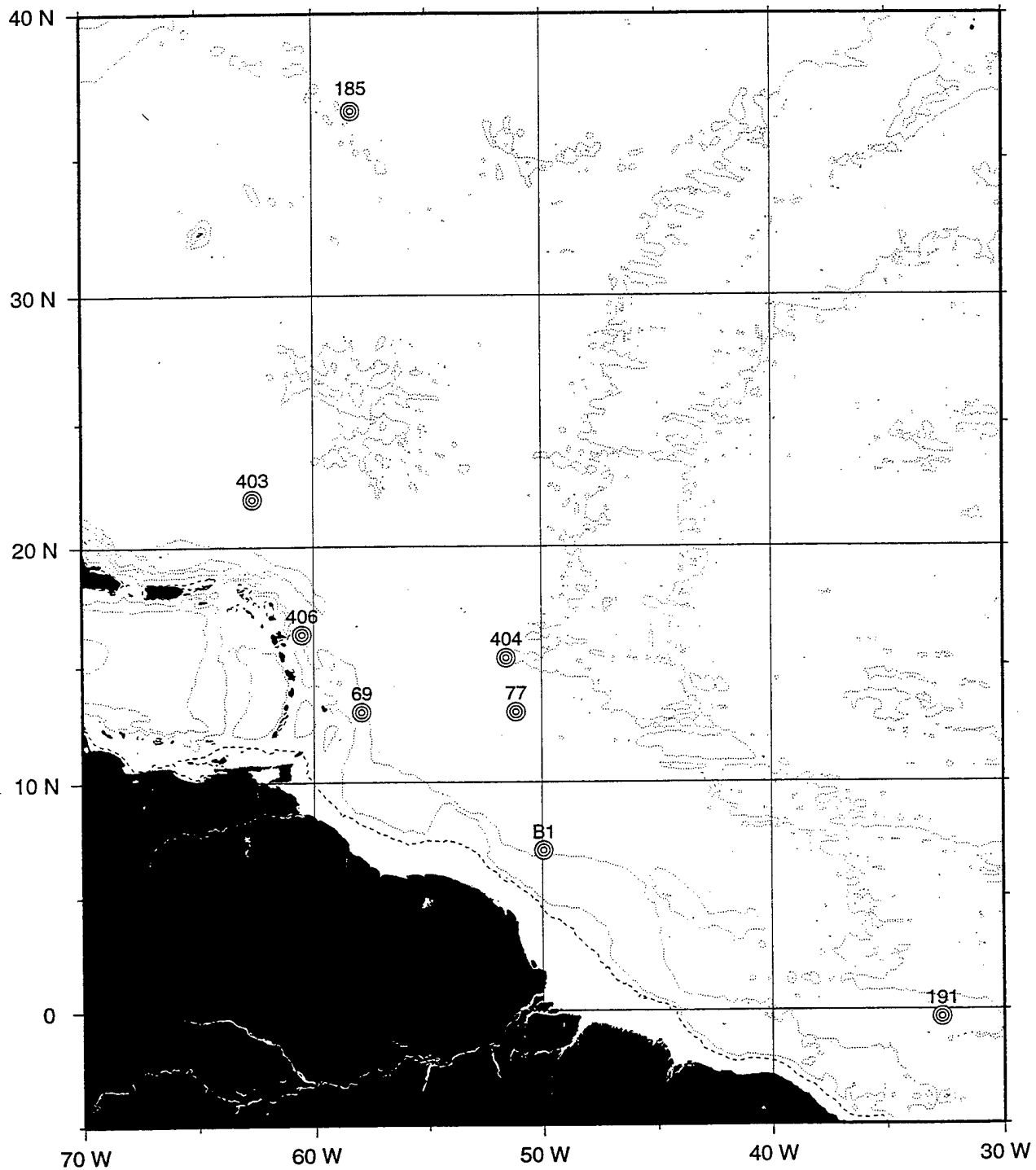


Figure 3. Locations of sound sources used in this experiment. Note that source 185 is located far to the north. The dashed line represents the 200 m isobath; dotted lines are isobaths in 2000 m increments.

The French source B1, deployed 950101, was used for nearly every float. Thanks to regular monitoring using MARVOR floats, Michel Ollitrault was able to supply a drift rate for B1's clock (personal communication).

Deep Basin Experiment source 191 (also called M1b) was used in a few cases. It was deployed February 12, 1995 (Hogg *et al.*, 1996; Hogg and Owens, 1999).

Two sources were deployed on the first NBC cruise and removed on the last cruise. They worked well, but were retrieved before the last float had surfaced (Figure 1).

Scientists from IFM, Kiel, deployed three sources in support of the Meridional Overturning Variability Experiment in January 2000. One was in the 0030 window, ponging at 0035, and was used in tracking only two floats (023 and 039) where it was heard in the 0100 window. The other two sources were used frequently in computing the latter sections of float trajectories. B1 wasn't recorded by most floats after the deployment of the MOVE sources. This is because the floats record the two strongest TOAs in a listening span, so B1 was pre-empted because it was third strongest.

In some cases, we relied on information derived on earlier experiments (Olaf Boebel *et al.*, 2000) for the sound velocity. When necessary, we estimated the sound velocity by dividing the distance between the source and the float launch position by the travel time computed from the first TOA.

## 5. Float Data Processing and Tracking

Floats were tracked by converting the TOAs into distances between floats and sound sources. The sound velocity for each source was specified in the source file (Table 4). Float positions were calculated by least squares triangulation, using distance time series from as many sources as were available, usually three. A spline was used to interpolate missing TOAs. In most cases, interpolation was limited to gaps under 10 days, but for two floats (024 and 032), the limit was increased to 20 days. A Doppler correction was applied to correct the TOAs for the distortion caused by the speed at which the float was travelling. No additional float-clock offsets were applied at tracking (see Table 3).

Two floats, 431 and 432, had their positions linearly interpolated to 12 hours to match the rest. Position time-series were then smoothed by means of a Gaussian-shaped filter ( $\delta=1$  day) with weights 0.007, 0.197, 0.590, 0.197, 0.007. Finally, a cubic-spline function was fitted through the positions and velocity series calculated along the trajectories.

In general, the time-series data and trajectories were of good quality. For some floats in a band around 13° N the tracking program either failed to compute positions or had increased position errors. At this latitude, off the Antilles, these floats heard only the two NBC sound sources. The difficulty occurred because the floats were near the extension of the baseline connecting the two sources. Other than in this area, we estimate position errors to be around 4 km, based on this and earlier float experiments. Several floats drifted into the Caribbean where tracking was impossible because the islands blocked the acoustic signals.

The NBC floats were tracked using ARTOA-II, a single integrated package of Matlab routines that makes it possible to track a float in a single session (Working Group, 2002), permitting corrections to be made in the rawest data. It represents a complete overhaul of previous programs and has been developed in stages by Claudia Schmid (at IFM, Kiel), Martin Menzel (IFM, then IFREMER in Brest), and Olaf Boebel (IFM, URI) (Anderson-Fontana *et al.*, 2001). Further enhancements were added by Heather Furey and Roger Goldsmith at WHOI.

One complication in tracking the DLD2s was that the windows were open for 27 minutes, but the DLD2 can only store 21 minutes (see Appendix A). This meant that the times of arrival could roll over within a window, as well as from one window to another. Careful attention had to be paid to source identification and to shifting the TOAs before selecting them.

RAFOS floats 431 and 432 had final clock drifts greater than 200 seconds. For float 431, the clock drift had to be prorated to the shortened mission:

431 start offset	1998 12 05 15 38 -23
431 end offset	1999 04 14 03 00 -67.31 (-206.4 overall)
432 start offset	1998 12 05 12 49 -24
432 end offset	2000 05 28 03 00 -258.03

## 6. Preliminary Results

All the figures referred to in this section are given in Appendix C. Displacement vectors are given in Figures C1-C8, and summary float trajectories in Figures C9-C12. A summary of float trajectories *after* surfacing is given in Figure C13. Figures C14-C19 pertain to floats in rings and eddies. The individual trajectories and time series are in Appendix D.

Floats at different depths drifted in somewhat different patterns. For example, six of nine 250 m floats entered the Caribbean, but only two of the 550 m floats and none of the 900 m floats did so (Figures C1-C8).

Fourteen of the floats looped in 17 rings and eddies (loopers) (Figure C14). A looper is defined as two or more consecutive loops in the same direction. There were also several instances of floats being advected by the outer portions of rings and eddies but not in consecutive loops. Some examples of long looping trajectories are float 029 in ring 1 (Figure C15), float 033 in ring 2 (Figure C16), float 193 in ring 5 (Figure C18), and float 036 in a long-lived deep cyclone (Figure C19). Ring numbers used here refer to rings observed on the cruises and tracked with drifters and floats. Many additional rings were observed by altimetry, ocean color images, moored current meters and the inverted echo sounder array.

Ring 2 (Figure C16) was the longest tracked ring at 14.3 months. Float 033 (at 320 m) looped in ring 2 for 7 months at a period of 6 days as it translated rather erratically northwestward at a mean velocity of 6.8 cm/sec. For another 7 months float 033 looped in ring 2 as it remained nearly stationary in the Tobago Trough. Because the ring was located near 13N near the baseline extension of the two sound sources during the last 7 months, float 033 could not be accurately tracked. However, the pattern of TOAs clearly shows the continuation of the looping and the approximate location (Figure C17). The implied 14-month lifetime of this ring is much longer than the usual 3-4 month lifetime of rings that were observed with surface drifters, altimetry and satellite ocean color images. This implies that the subsurface portions of other rings might also last longer than the nominal 3-4 months.

The second longest tracked eddy was a deep (900 m) cyclone observed for 10.5 months as it translated erratically northwestward at a mean velocity of 3.2 cm/sec. Float 036 (at 860 m) looped 78 times with a mean period of rotation of 4 days (Figure C19). Two other floats (022, 023) also looped in this cyclone. During the launch cruise the cyclone was in close proximity to ring 3; three of the floats thought to have been launched in ring 3 were actually in the cyclone.

The surface drifters revealed that ring 3 translated westward, but the cyclone went northwestward clearly showing that the eddies separated. These measurements suggest that deep cyclones can occur in the ring region, possibly related to rings.

Often several rings were observed and tracked simultaneously. An extreme example occurred in March 1999 when floats and drifters looped in what look like 4 different rings and the deep cyclone. Ring 1, tracked by float 029 near 59.5W, translated northwestward near Barbados and was probably colliding with it. Ring 2, tracked by float 033 near 57.5W, translated northeastward. Ring 3, tracked by surface drifters near 9.5N, translated fast westward (54W-58W). Ring 4, tracked by a surface drifter near 8N 51W was in the formative stage and translated northwestward. The cyclone, tracked by floats 022, 023, and 036, near 10N 53W, translated northwestward. The close proximity of these eddies suggests that they were probably interacting with each other.

Several interactions between rings are implied by the trajectories. The surface drifters in ring 2 left this ring and were advected around the west side of ring 1. This occurred just when float 033 (at 320 m) in ring 2 translated northeastward and ring 3 translated fast westward on the south side of ring 2. After ring 3 had passed by ring 2, ring 2 returned to the southwest. The northeastward deflection of ring 2 appeared to be caused by its advection around the periphery of ring 3 as ring 3 translated up the coast. Ring 4 appeared to collide with ring 2 which might have caused the destruction of ring 4. At least the drifters and floats stopped looping in ring 4 and were advected around the west side of ring 2. The implication is that ring-ring interactions occur frequently and they are important to the evolution of rings.

Rings collided and interacted with topography on several occasions, especially toward the end of their lives as they approached the Antilles. The centers of rings 3 and 5 translated over or very close to Barbados as indicated by looping surface drifters and also SeaWiFS imagery (Fratantoni and Glickson, 2002). The swirl velocity in these rings entirely engulfed Barbados at these times.

The preliminary results mentioned briefly here need to be further investigated by merging the float trajectories with the surface drifter trajectories, ocean color images, altimetry, and the data obtained on the cruises and from the moored arrays. This work has just begun.

## 7. Acknowledgments

The assistance of the captain and crew of the *R/V Seward Johnson* is gratefully acknowledged. We thank the participants of the four NBC Ring cruises for their help in launching sound sources and floats. Thanks to Richard Limeburner and John Whitehead for launching a float from *R/V Oceanus* on cruise 3853. We thank the members of WHOI's Float Operations Group, James R. Valdes, Brian J. Guest, and Robert D. Tavares, for assembling, ballasting, and testing the floats. Financial support for this research program was provided by the National Science Foundation through Grant No. OCE-9729765 and OCE-0136477.

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## Appendix A:

### Description of the DLD2 RAFOS Float

The Deep Lagrangian Drifter 2 is a second-generation RAFOS float using individual electronic modules for each basic function (timekeeping, e.g.). It also has more-accurate pressure and temperature sensors and clocks and a lower power requirement than the previous WOCE version. Demodulation of the acoustic signal is entirely digital.

It is easier to vary the mission of DLD2s than the previous generation. Nominally, a single 24-hour session is opened each day and collection of TOAs and Ts and Ps can be distributed throughout the 24-hour schedule (limited by a maximum of 24 actions, and by the 256-bit Argos-message size).

Temperature and pressure are converted to engineering units by the float using stored calibration constants, including the temperature dependence of the pressure sensor. Pressure accuracy is 0.1% of full scale (or better), and temperature accuracy is 0.01°C between 0 and 32°C.

The DLD2 floats can store message-numbers up to 2048, where the earlier floats could only store values up to 256. This simplifies computations and removes the uncertainty when gaps are filled with messages with bad checksums (the checksum was used to decide whether a message-number was greater than 256).

At completion of the mission, messages are divided into 10 packets. All first messages from all 10 packets are transmitted, followed by a status message, then all second messages, etc. This achieves the goal of transmitting information from throughout the mission in a short interval, without the shuffling algorithm used by the older RAFOS floats. (Null messages are used to fill incomplete packets.)

The status message includes a number of engineering parameters and system flags. The data is in two parts: information recorded at the end of the mission, and information recorded at the time the message is sent. Thus one can watch the battery voltages drop over time, or obtain a sea-surface temperature record. The status message gives the temperature and pressure in full (two bytes). The values for the end of the mission thus provide targets to compare to the lower-resolution values in all other messages. Non-status values are modulo 4.096 deg in temperature and 409.6 dBars for pressure.

The status message also records the internal clock. Thus, the final clock offset can be calculated directly by comparing the internal clock and the external, Argos clock.

Note that NBC used 260 Hz receivers, with a sampling period of 0.3075 seconds, so TOAs are modulo 1260 seconds. This means that they can roll over within a window, as well as from one window to another.



## **Appendix B:**

### **Two Additional Floats.**

Two floats that were processed differently from most are included here. They are the ALFOS float (number 017), which was launched November 12, 1998, and was last heard on October 2, 2000, and a test-float which was deployed on a BBTRE cruise in 1998 (one of 3 deployed: the second went too deep and surfaced after a day; the third was too shallow and heard only two sources sparsely).

These two floats were processed using ARTOA/ARTRK, the Matlab-GUI predecessor to ARTOA II. ARTOA/ARTRK used a single sound velocity for all steps of processing. For these two floats, that value was 1484 meters per second.

The ALFOS float surfaced every 10 days, transmitted for one day, and then submerged again. It used the transfer of oil between internal and external bladders to alter its vertical displacement, allowing it to surface and then return to its target depth of 800 meters. The overall range of this ALFOS' drift depth was less than 100 meters, better than many of the other floats.

The ALFOS float was useful in confirming which sources were being heard, and its results were shared with colleagues in Germany and France. It was in the ALFOS record that we first recognized the appearance of the oldest sources, from the BOUNCE experiment.

The ALFOS float listened at the same times as the bulk of the NBC floats, 0100, 0130, 0200 twice a day. A float clock-drift was computed each time it surfaced. A program applied the clock-drift to the TOAs and renumbered the records consecutively to permit tracking it.

ALFOS float 017 was processed using sources 69, 77, 185, 199 (DBE), 404, and 406. Because of the one-day-in-ten on the surface, the acoustically tracked portion could be checked against the locations reported by Service Argos. Occasionally, an expedient additional clock drift was used to improve agreement. Gaps in the subsurface track were linearly interpolated, but no smoothing was done.

Float 007, the test float, was processed using DBE sources 192, 193, and 194. It listened at 0030, 0100, and 0130 daily. The computed locations were interpolated to a 12-hour interval before smoothing.

### Statistics:

	Launch			Surface			Target	Mean	Mean
	Date	Lat	Lon	Date	Lat	Lon	Depth	Temp	Depth
	yymmdd	° N	° W	yymmdd	° N	° W	m.	° C	m.
	<b>ALFOS Float</b>								
017	981112	10.802	52.232	001002	18.587	58.909	800	5.77	957.4
	<b>DLD2 Float</b>								
007	980313	-11.050	31.250	990313	-7.971	30.841	800	4.48	809.7

### Performance:

	Offsets (secs)		Messages	%	Trackable	Sources
	Initial	Final	Received		Months	Heard
017	0.00	-27.77	689/690	100	24/24	7
007	0.00	4.90	365	100	12/12	7

### Sound Source Information (additional DBE sources):

ID	Pong	Corr	Rep	Start	End	Offset	Drift	Depth	Lat	Lon	S.V.
	Time	(min)	Rate	Date	Date	(sec)	(sec/rep)	(m)	° N	° W	(m/sec)
192	0030	30	24	950213	none	0.0	0.000	1000	3.707	31.209	1484
193	0030	30	24	950219	none	0.0	0.006	1000	11.297	20.012	1484
194	0100	00	24	950223	none	0.0	0.005	1000	14.094	30.061	1484
199	0130	-30	24	950408	none	0.0	0.004	1000	2.848	21.400	1484

**Appendix C:**  
**Summary float trajectories and composites, showing preliminary results**

Launch positions are marked with a circle and plus sign and end positions with a circle-dot and the float ID. Float tracks are solid black lines. A dashed line represents the 200 m isobath, and dotted lines are isobaths in 2000 m increments.

# NBC RAFOS Float Displacement Vectors

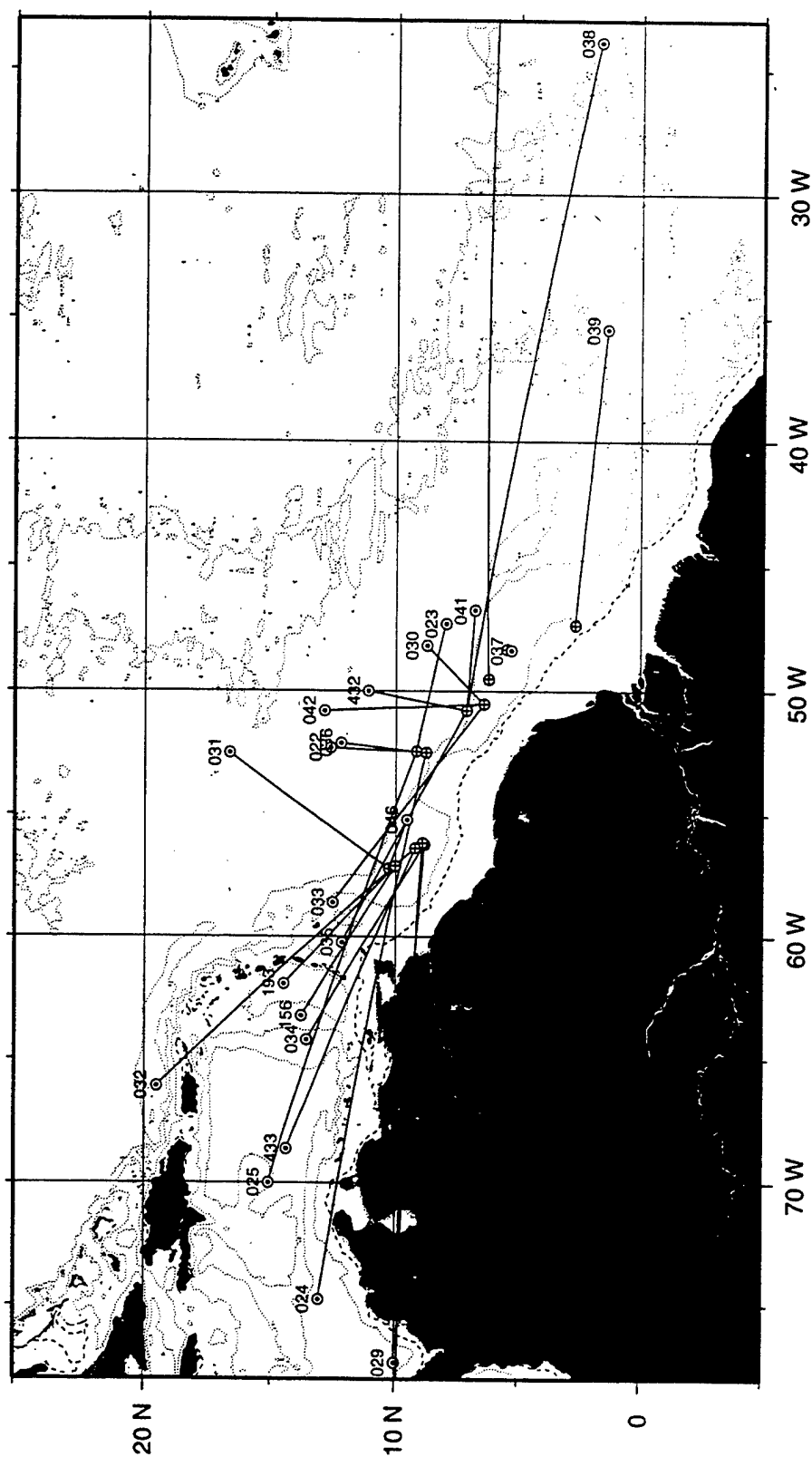


Figure C1: Displacement vectors for all RAFOS floats, deployment to surfacing location.

# NBC RAFOS Float Displacement Vectors at 250 m

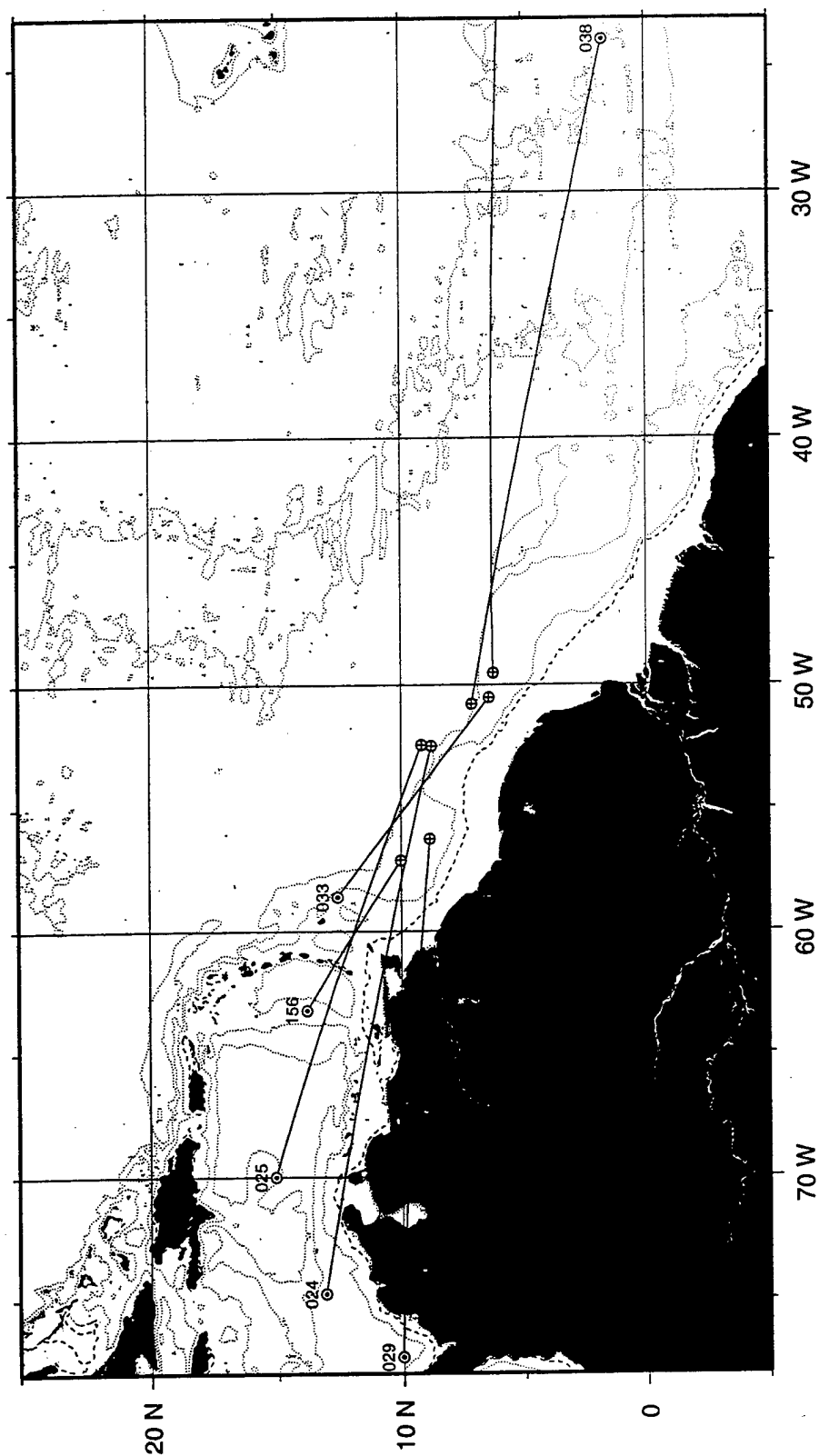


Figure C2: Displacement vectors for RAFOS floats at 250 meters, deployment to surfacing location.

# NBC RAFOS Float Displacement Vectors at 550 m

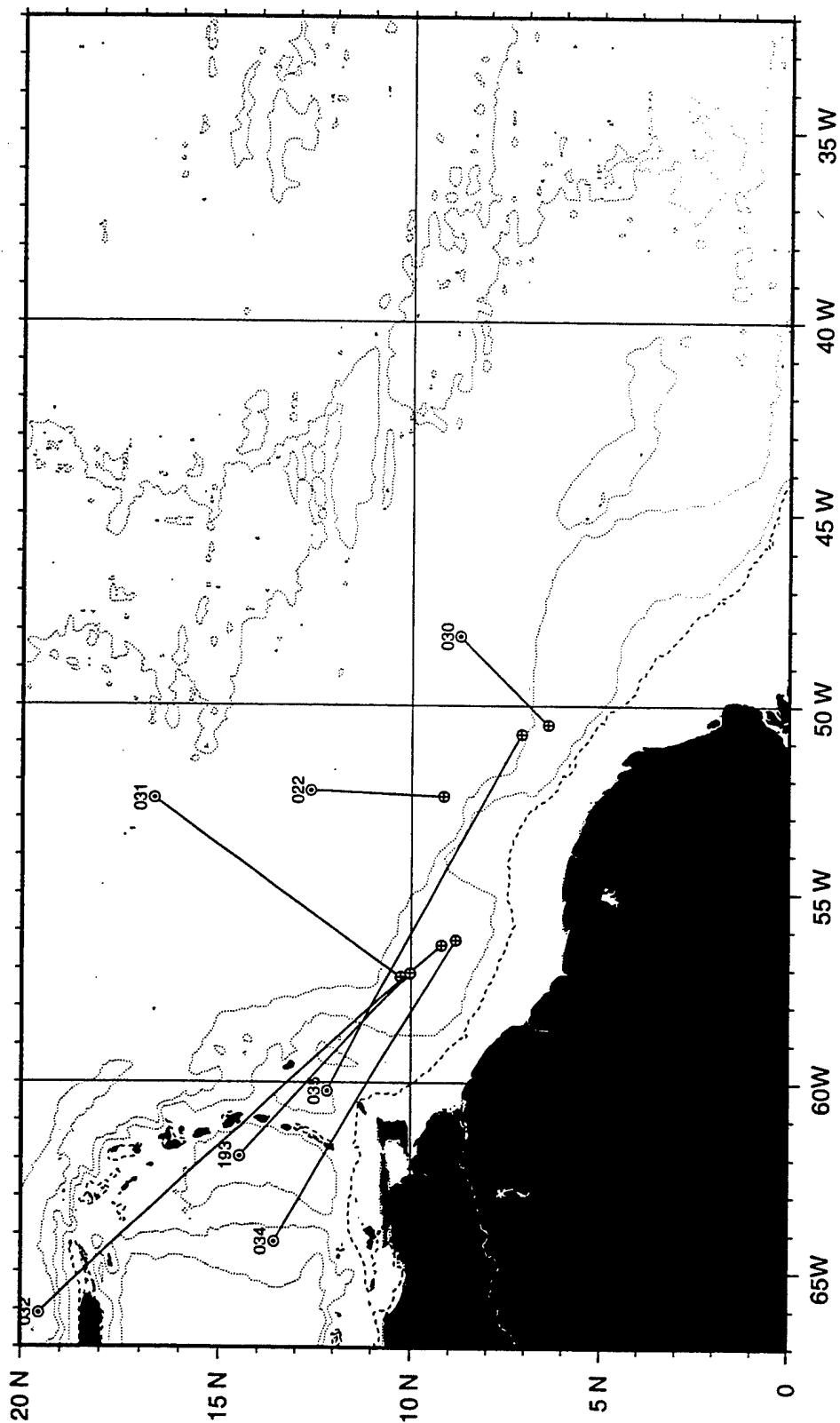


Figure C3: Displacement vectors for RAFOS floats at 550 meters, deployment to surfacing location.

# NBC RAFOS Float Displacement Vectors at 900 m

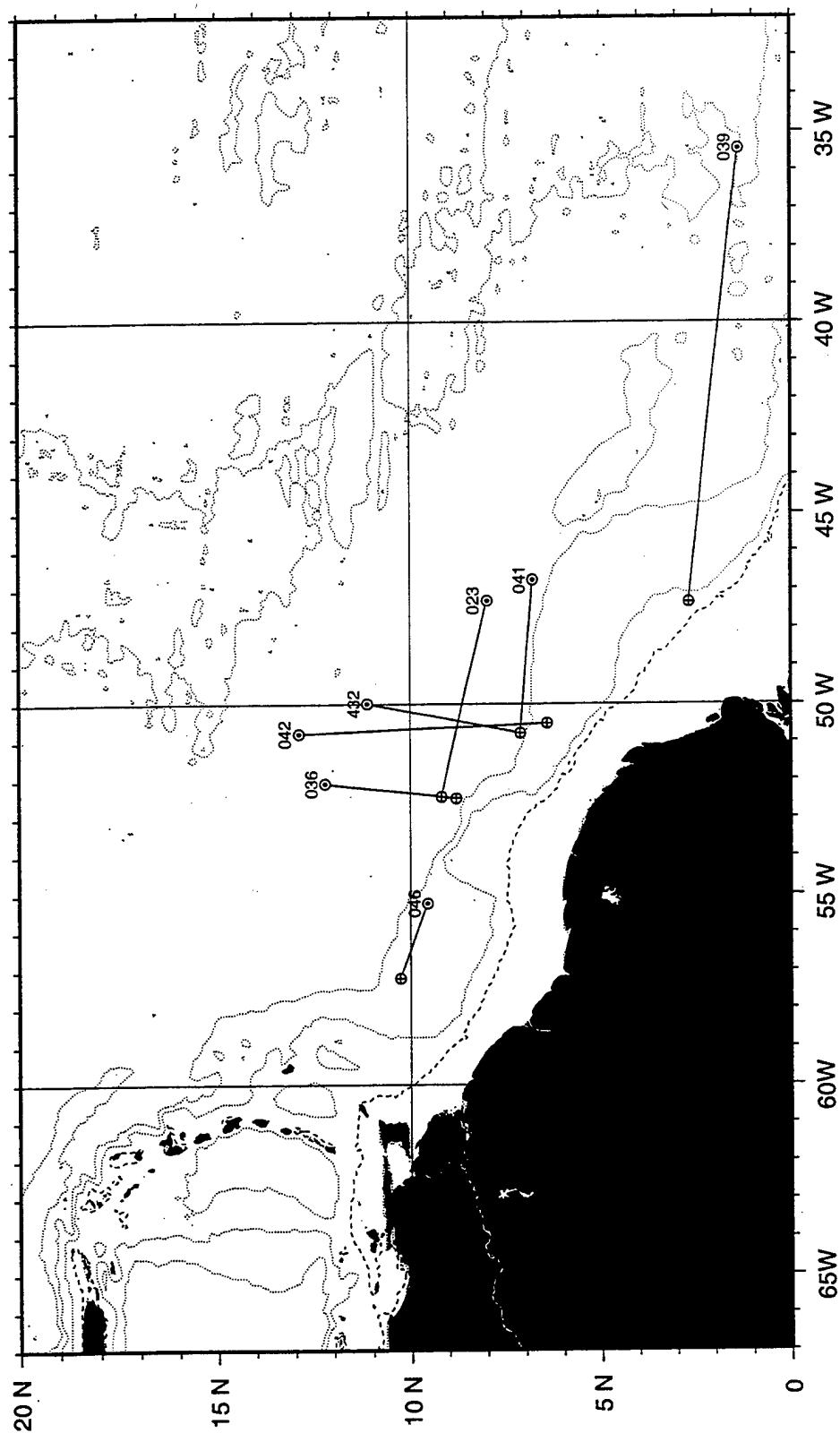


Figure C4: Displacement vectors for RAFOS floats at 900 meters, deployment to surfacing location.

# NBC RAFOS Float Displacement Vectors (Tracked Part)

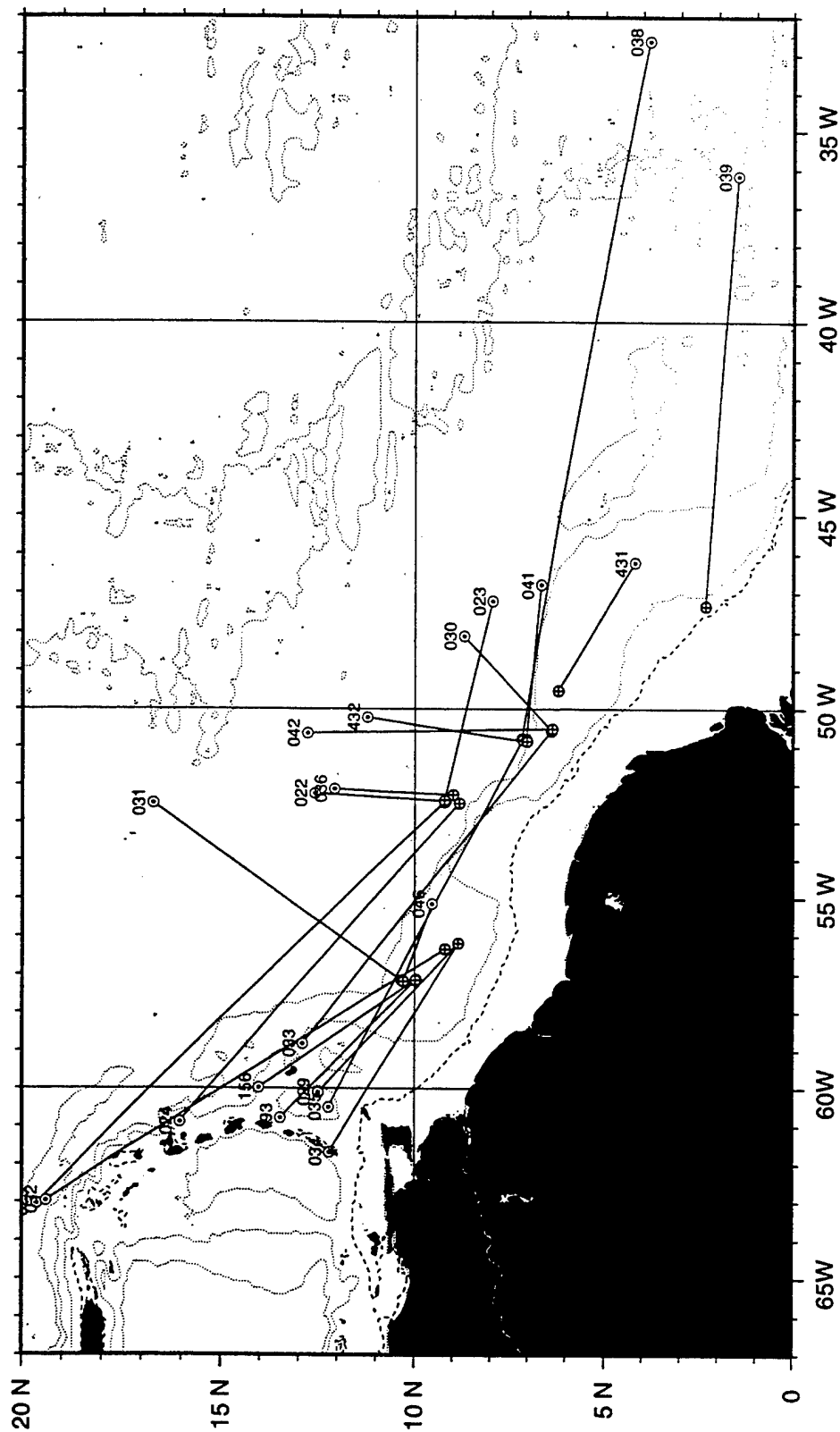


Figure C5: Displacement vectors for all RAFOS floats, acoustically tracked part.



# NBC RAFOS Float Displacement Vectors at 250 m (Tracked Part)

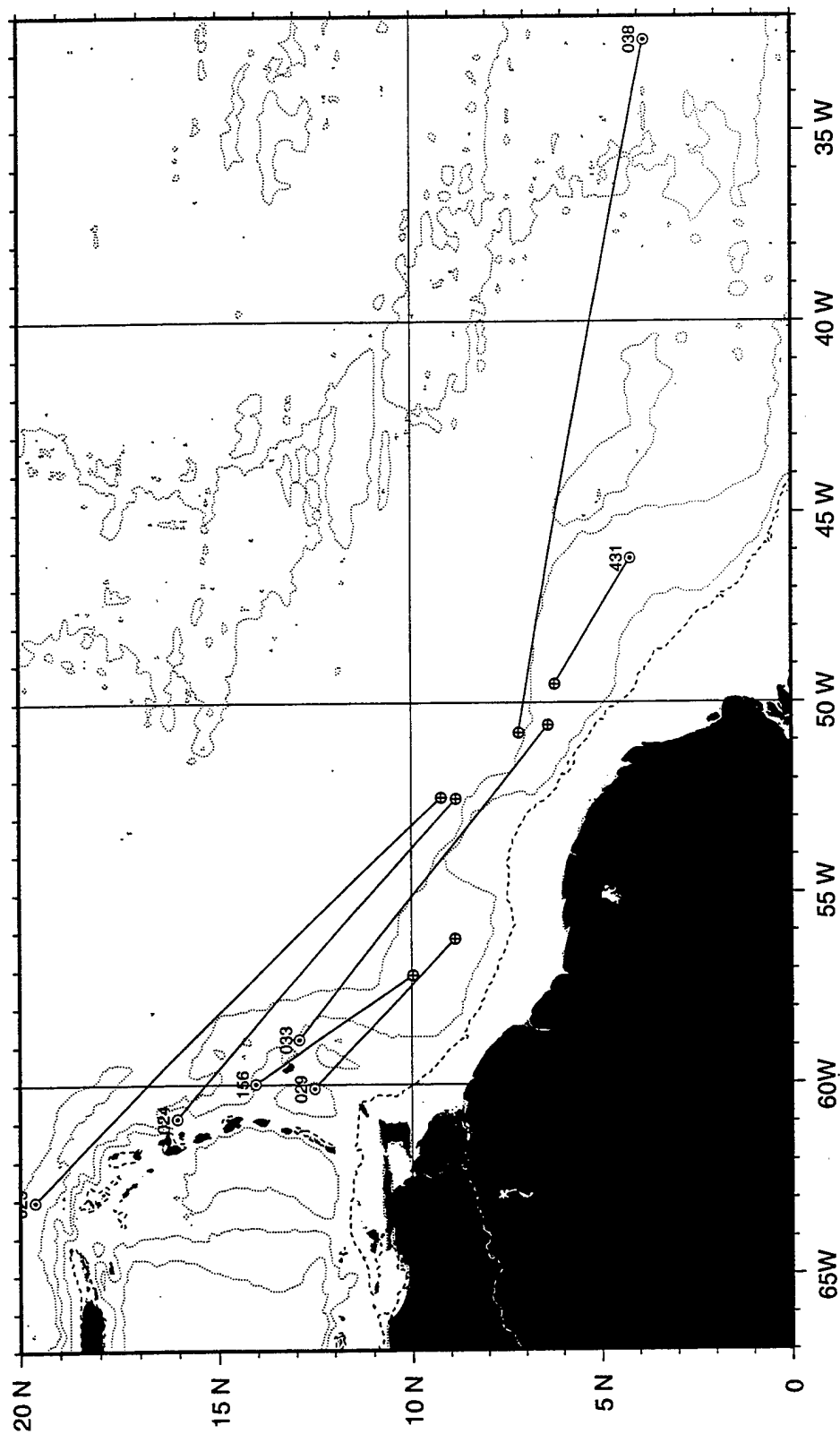


Figure C6: Displacement vectors for RAFOS floats at 250 meters, acoustically tracked part.

NBC RAFOS Float Displacement Vectors at 550 m (Tracked Part)

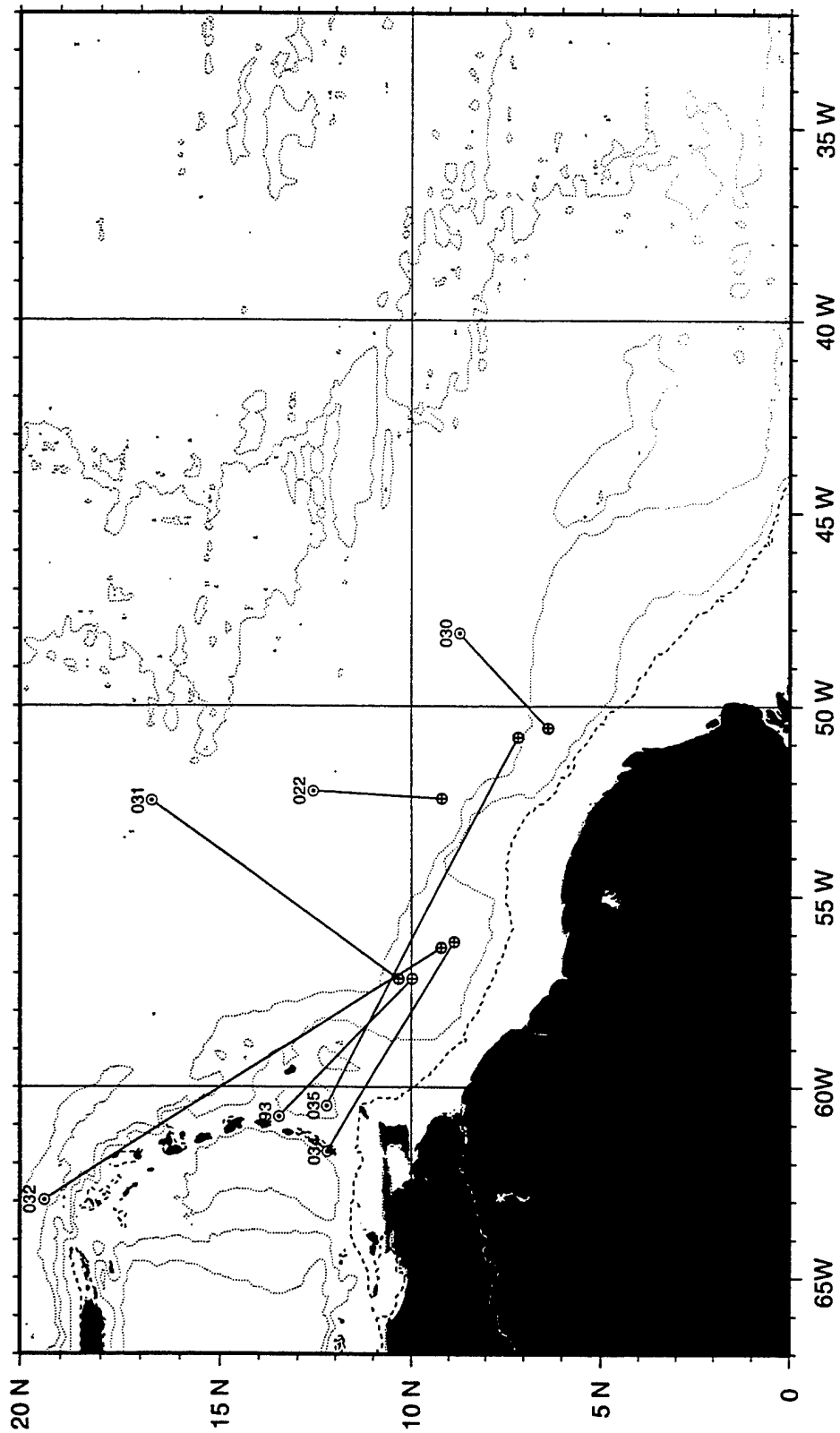


Figure C7: Displacement vectors for RAFOS floats at 550 meters, acoustically tracked part.

# NBC RAFOS Float Displacement Vectors at 900 m

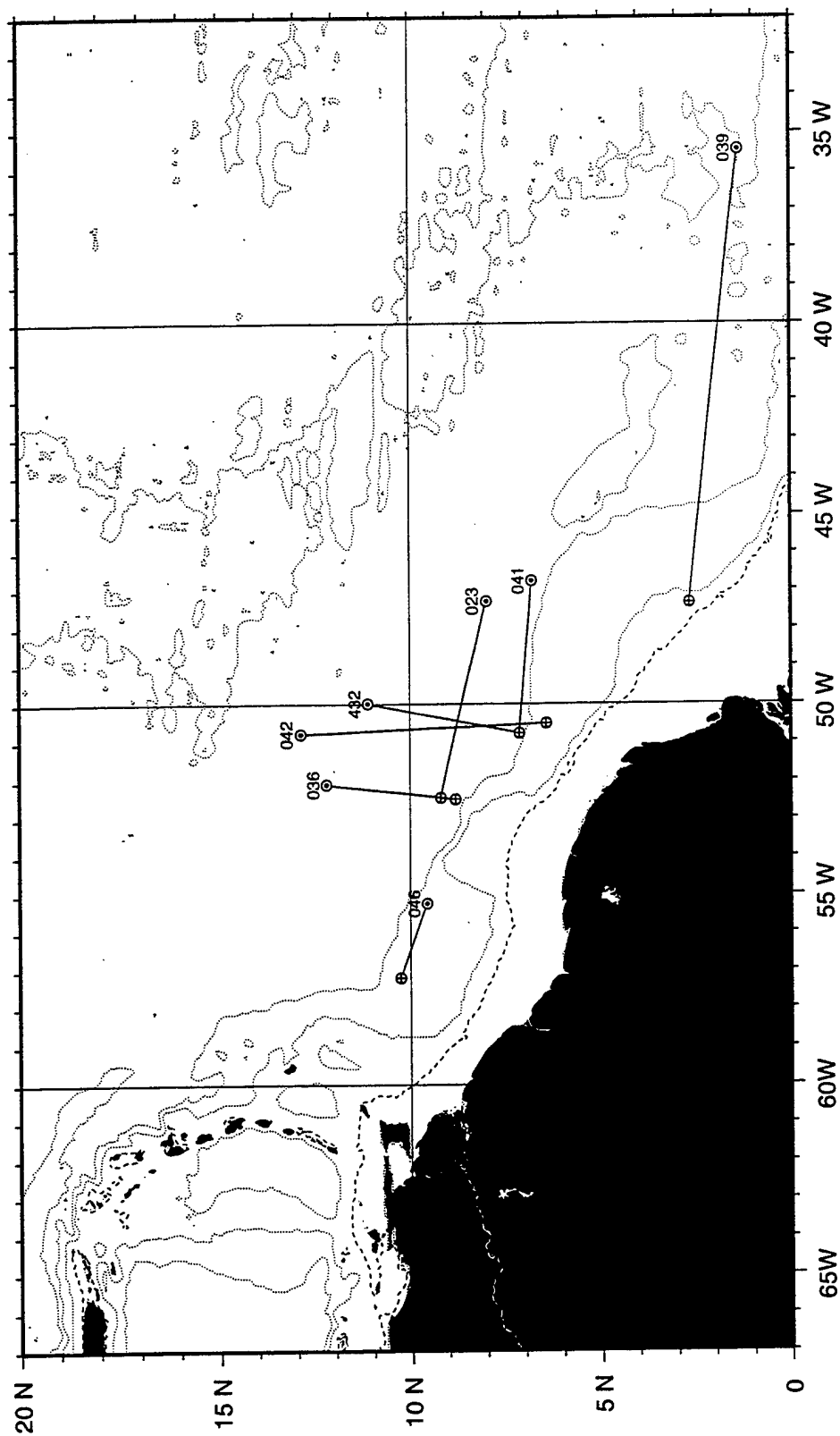


Figure C8: Displacement vectors for RAFOS floats at 900 meters, acoustically tracked part.

Composite of all NBC RAFOS Float Trajectories

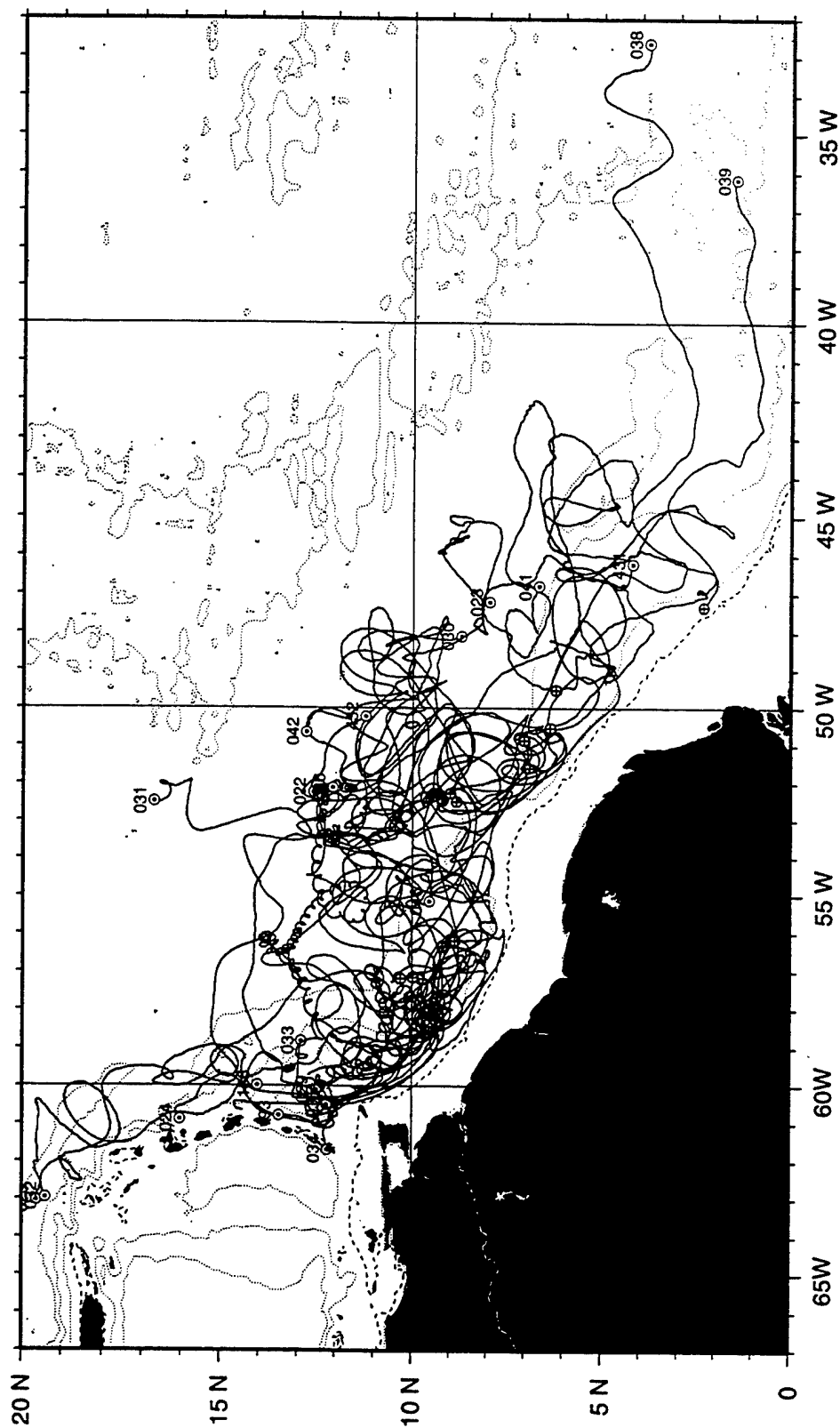


Figure C9: Summary plot of all RAFOS float trajectories.

# NBC RAFOS Float Trajectories at 250 m

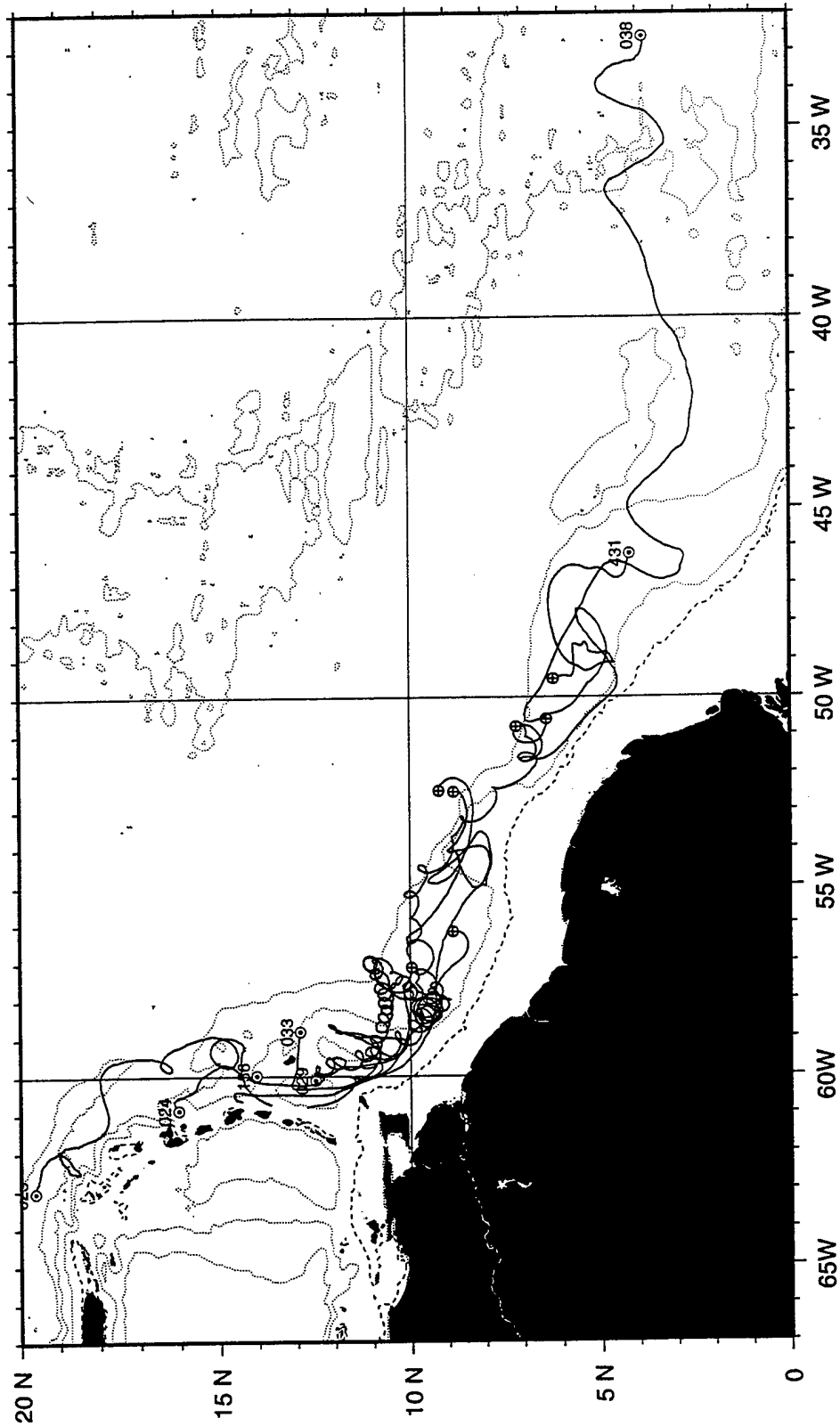


Figure C10: Summary plot of RAFOS float trajectories at 250 meters.

NBC RAFOS Float Trajectories at 550 m

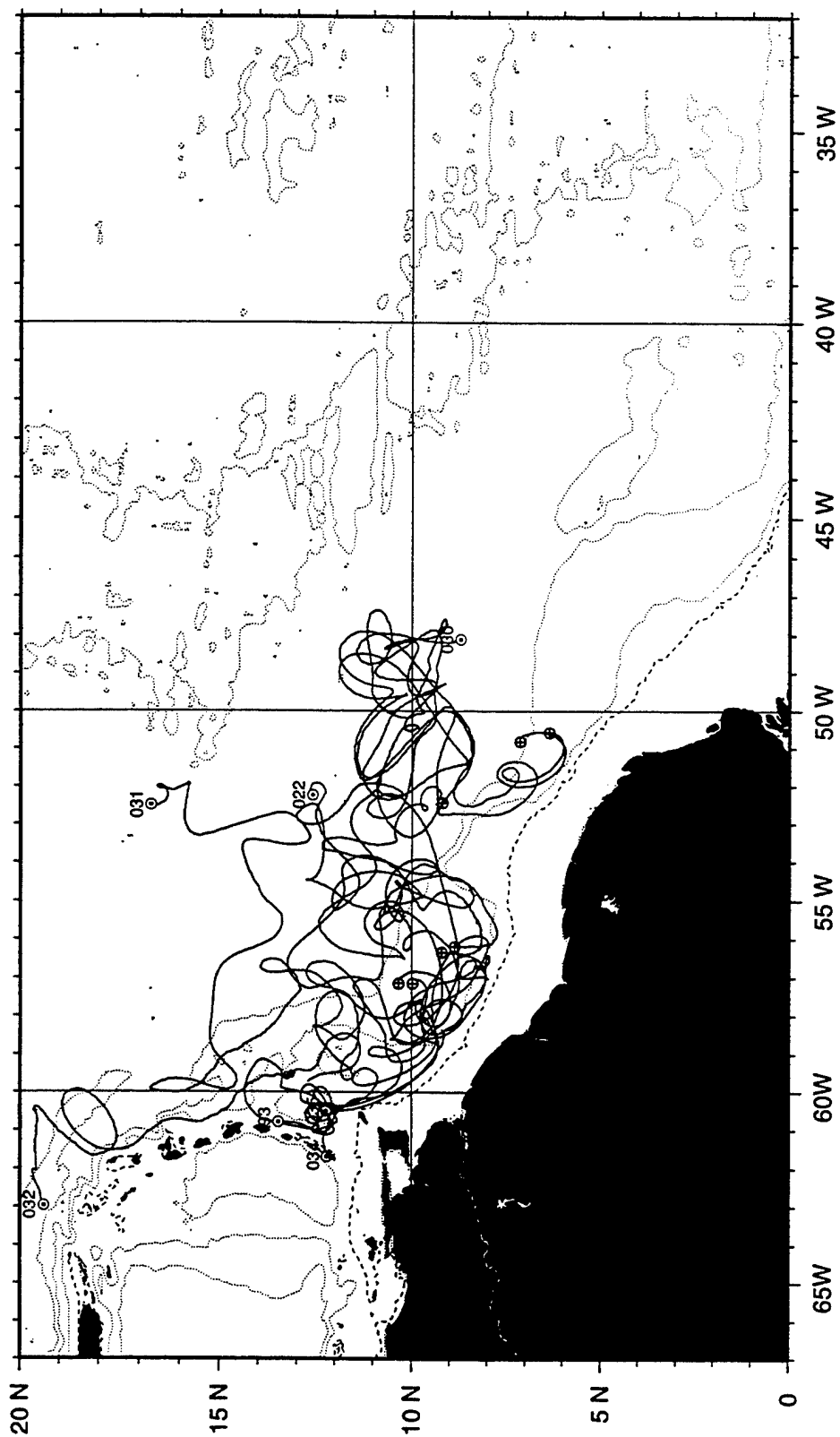


Figure C11: Summary plot of RAFOS float trajectories at 550 meters.

# NBC RAFOS Float Trajectories at 900 m

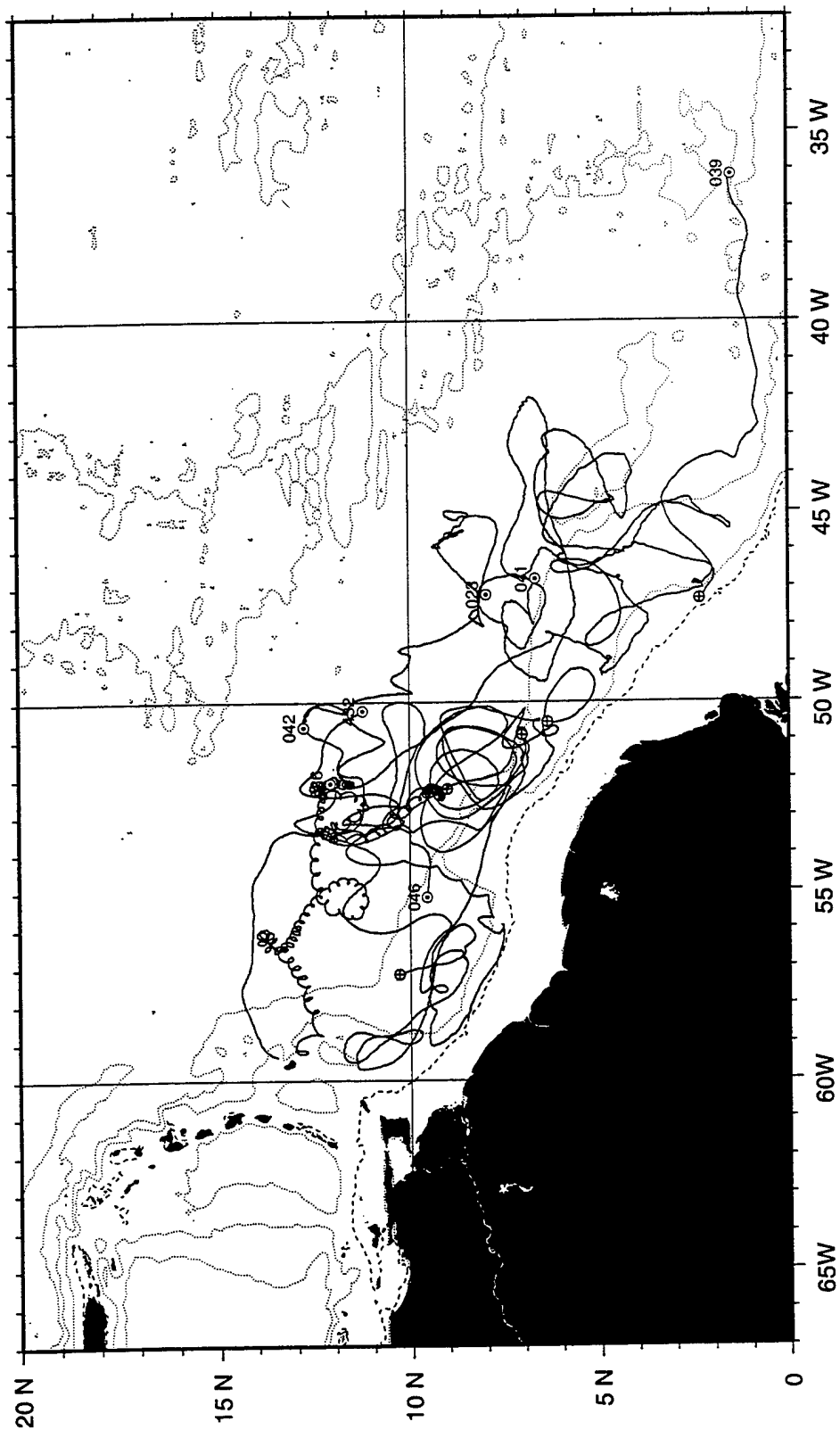


Figure C12: Summary plot of RAFOS float trajectories at 900 meters.

# NBC RAFOS Float Trajectories after Surfacing

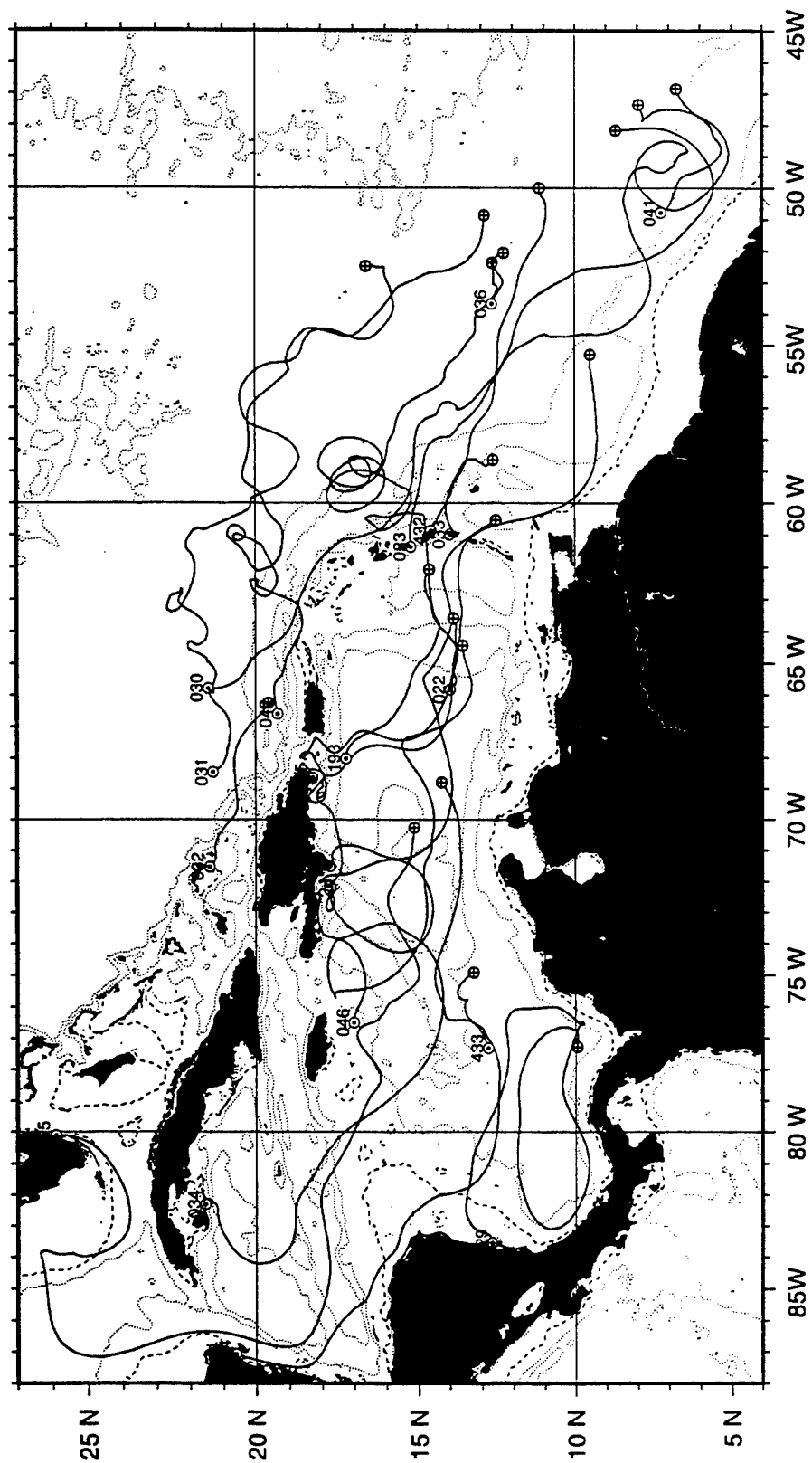


Figure C13: A summary of float trajectories *after* surfacing, tracked by satellite.



## NBC RAFOS Looping Float Trajectories

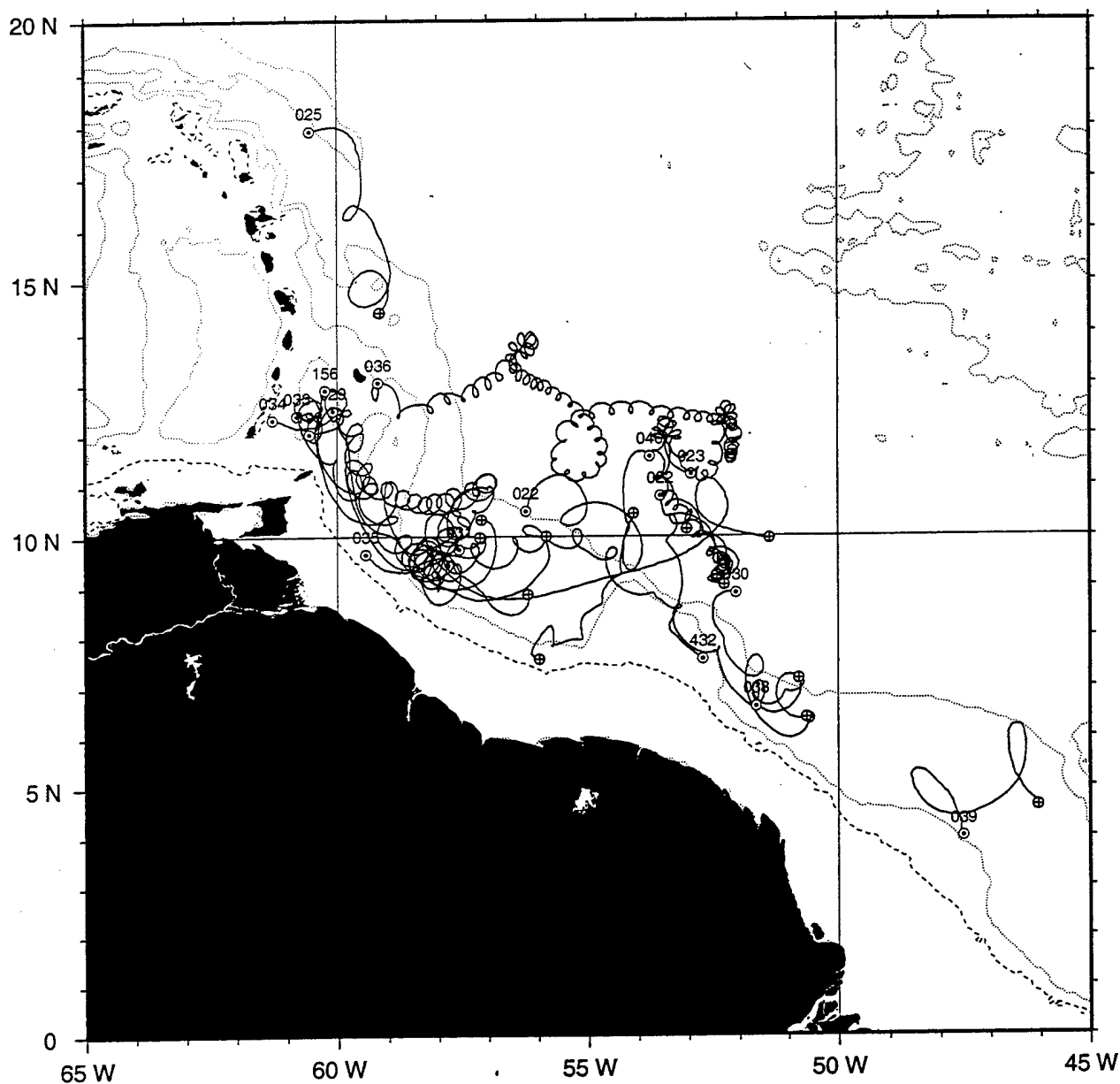


Figure C14: Trajectories of floats that made (roughly) two or more loops in the same direction. Seventeen loopers are superposed here. Small cross marks the beginning and small dot the end of each looper.

# NBC Float 029 Looping Trajectory

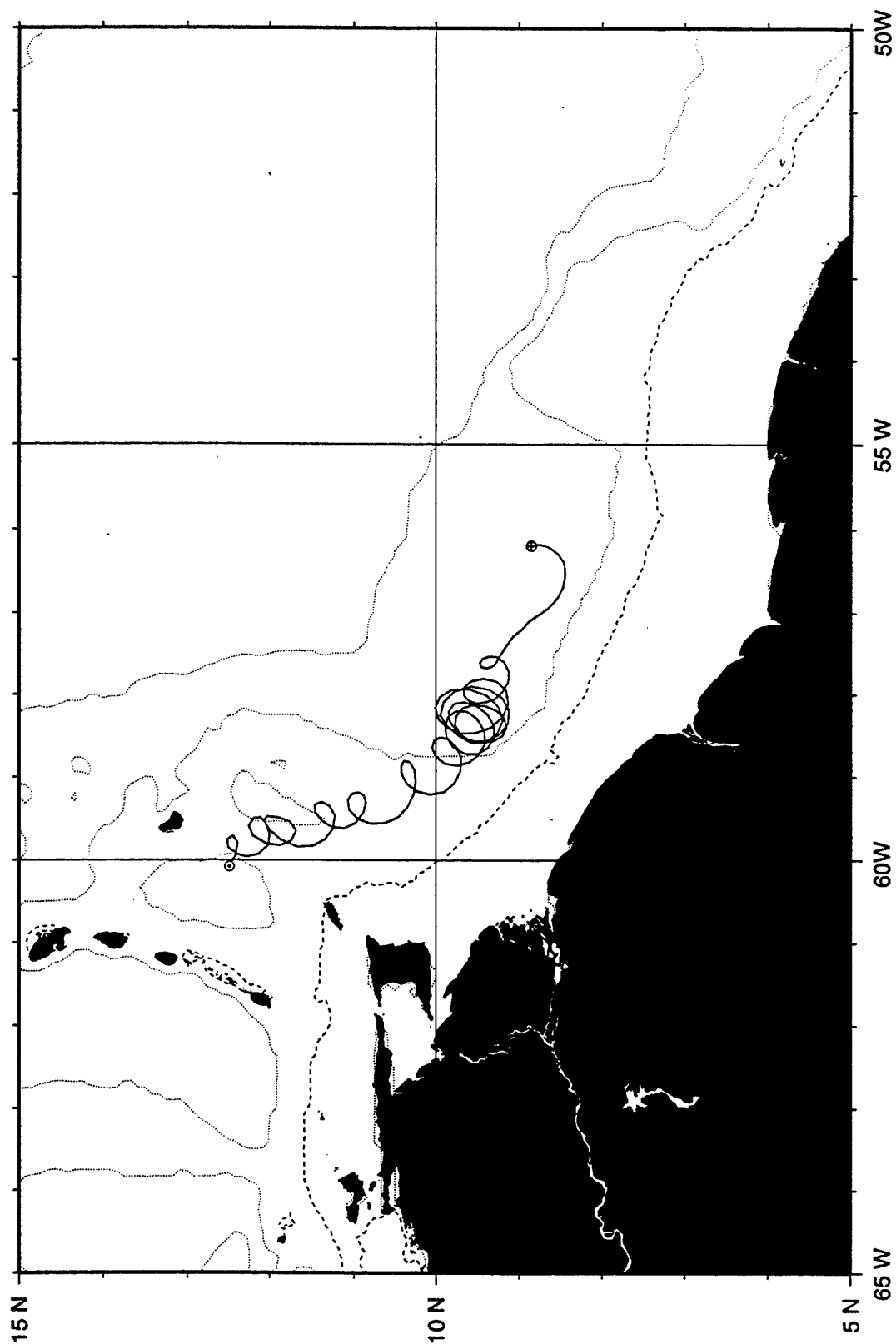


Figure C15: Float 029 looping at a depth of 270 m in ring 1. The cross marks the start and the dot marks the end of the loop.

# NBC Float 033 Looping Trajectory

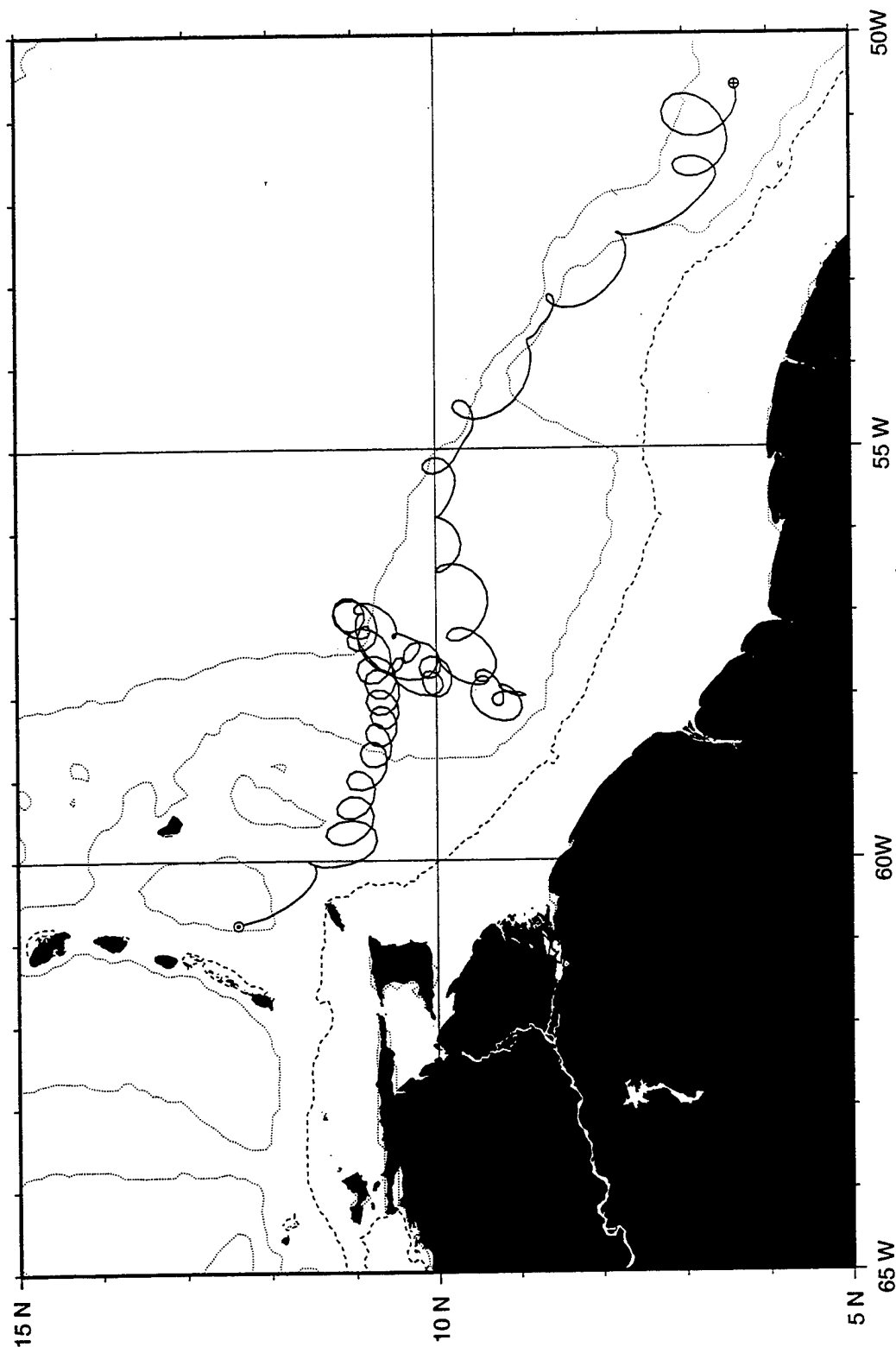


Figure C16. Float 033 looping at a depth of 310 m in ring 2. This float continued to loop near where the trajectory stops as observed by oscillations in the times of arrival (Figure C17). The cross marks the start and the dot marks the end of the loop.

### TOAs for Float 33

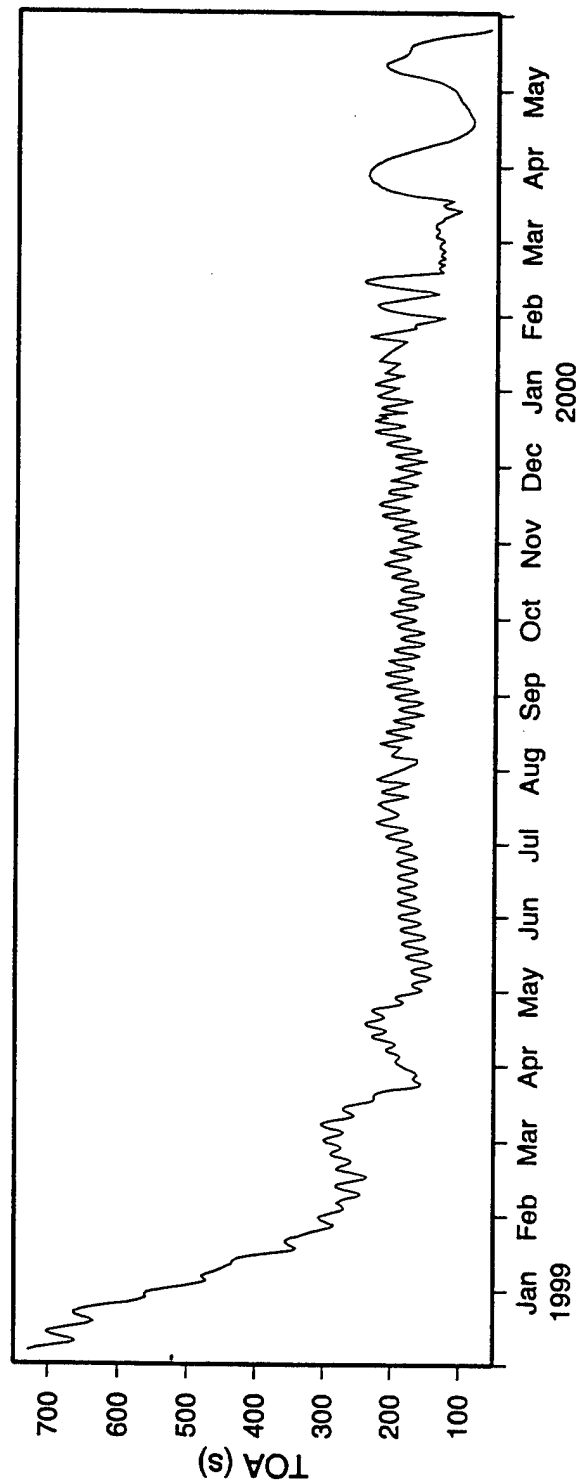


Figure C17: Times of arrival of source 69 as received by float 033. This float looped continuously in an NBC ring from December 1998 to February 2000 as indicated by oscillating TOAs. A few gaps in the record resulted in some jagged oscillations. It was not possible to track float 033 from July 1999 to March 2000 because the ring was located near the baseline extension of the only two sound sources heard.

# NBC Float 193 Looping Trajectory

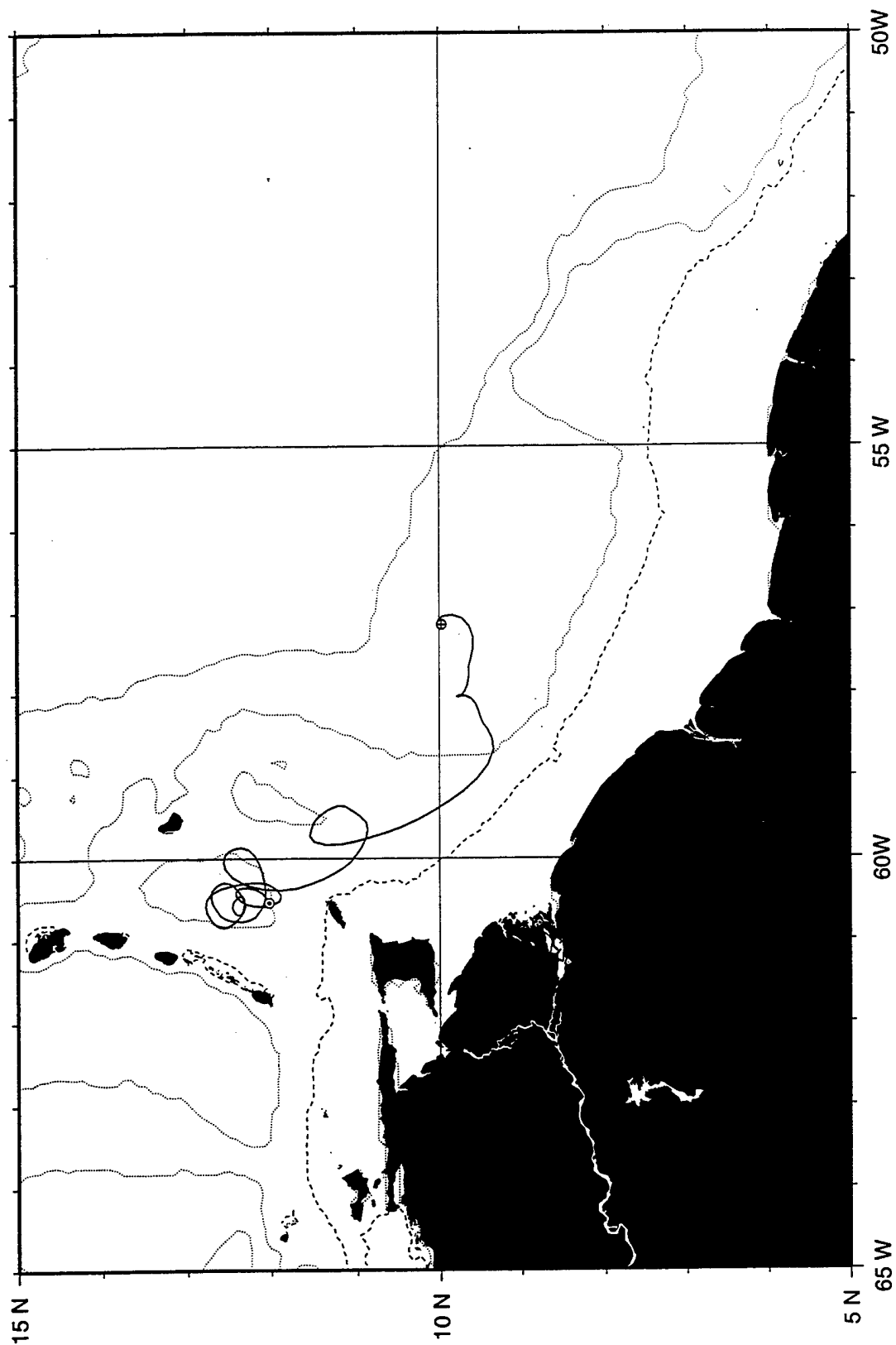


Figure C18: Float 193 looping at a depth of 500 m in ring 5. The cross marks the start and the dot marks the end of the looper.

# NBC Float 036 Looping Trajectory

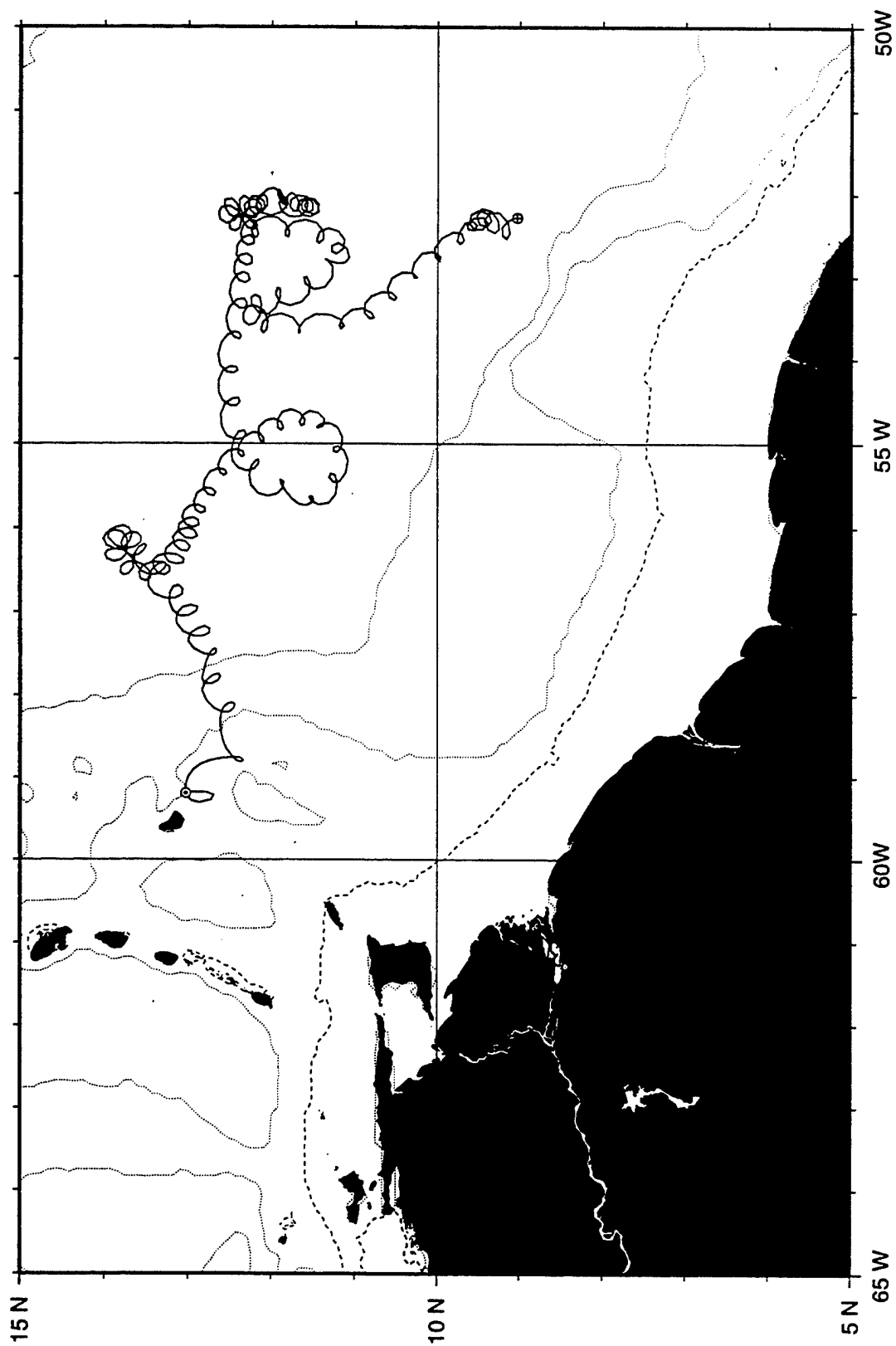


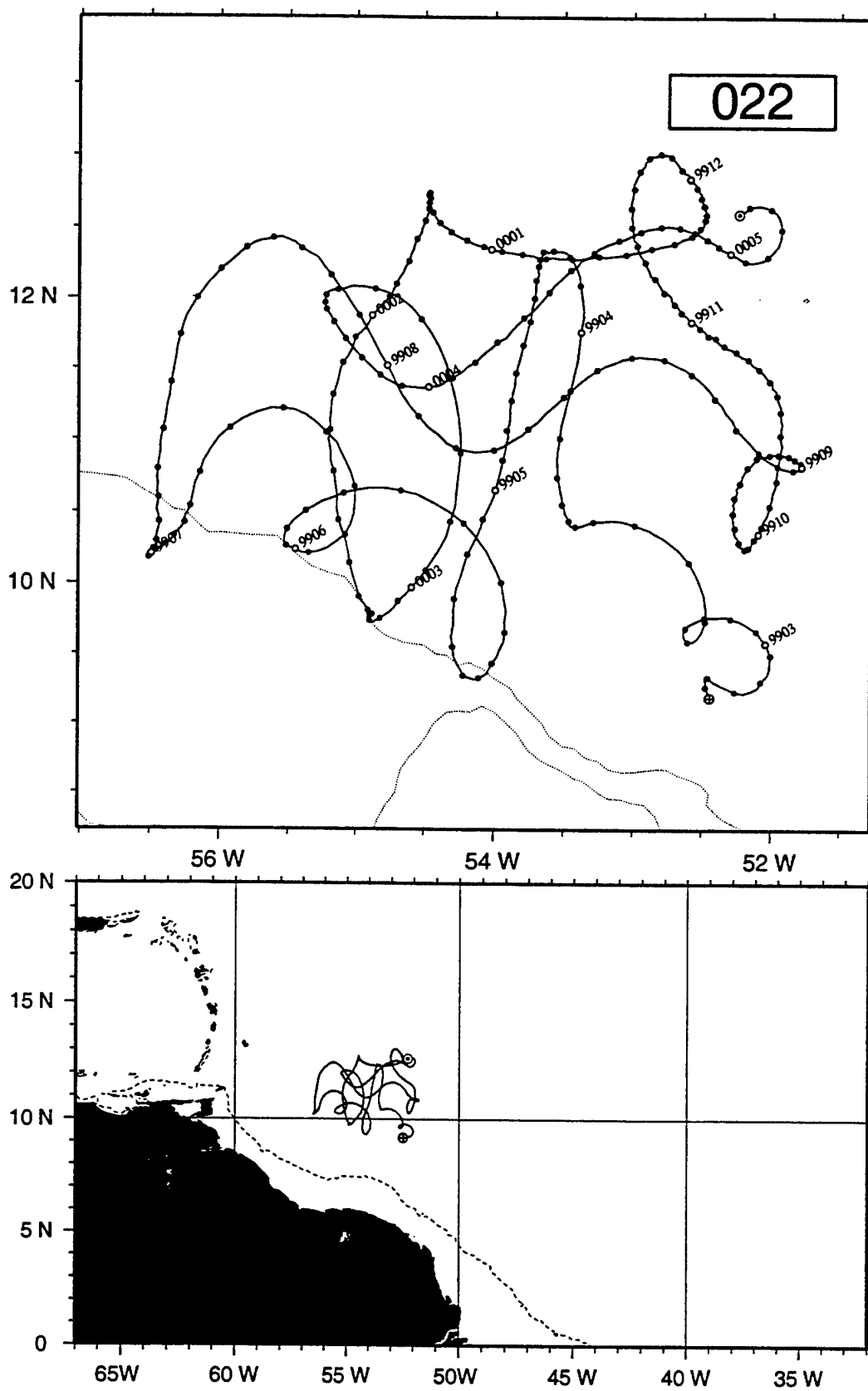
Figure C19: Float 036 looping at a depth of 850 m in the deep cyclone. The cross marks the start and the dot marks the end of the looper.

## **Appendix D:**

### **Individual float tracks and float property plots.**

The following section presents individual float trajectories and temperature, pressure, and velocity time series measurements. The trajectories are presented at a large, flexible scale (top) to show detail, and at a fixed scale (bottom) for comparison to other floats. The larger plots have closed circles every two days and monthly labels, with open circles. Bathymetry is represented by a dashed line for the 200 m isobath and dotted lines at 2000-meter intervals. Time ticks and isobaths (except at 200 m) have been omitted from the fixed scale plots.

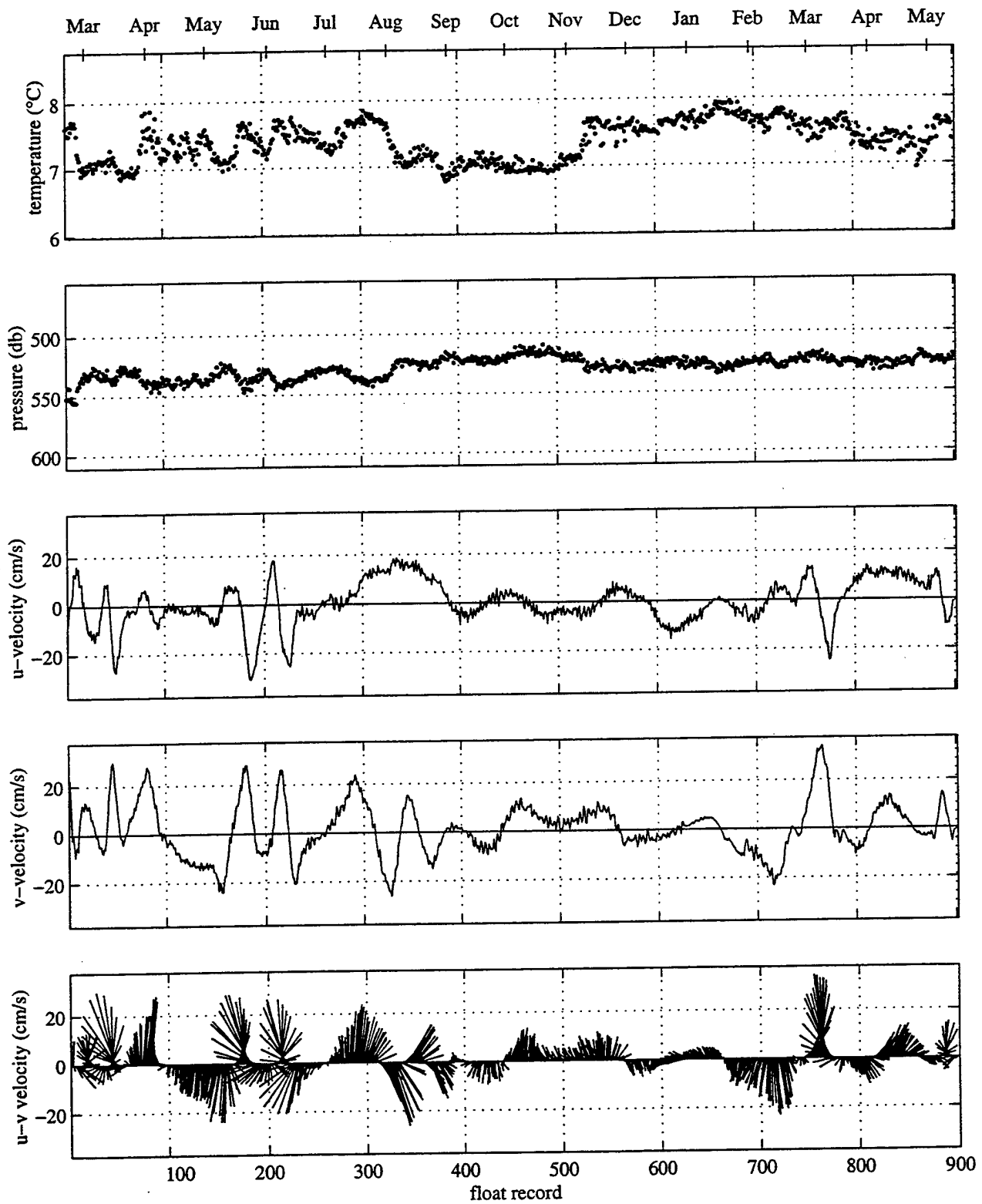
Float property plots show temperature, pressure, u (east) velocity, v (north) velocity, and velocity stick diagrams. Measurements were interpolated to twelve-hour intervals when needed. The upper x-axis shows a Gregorian calendar corresponding to the record day in the lower x-axis.

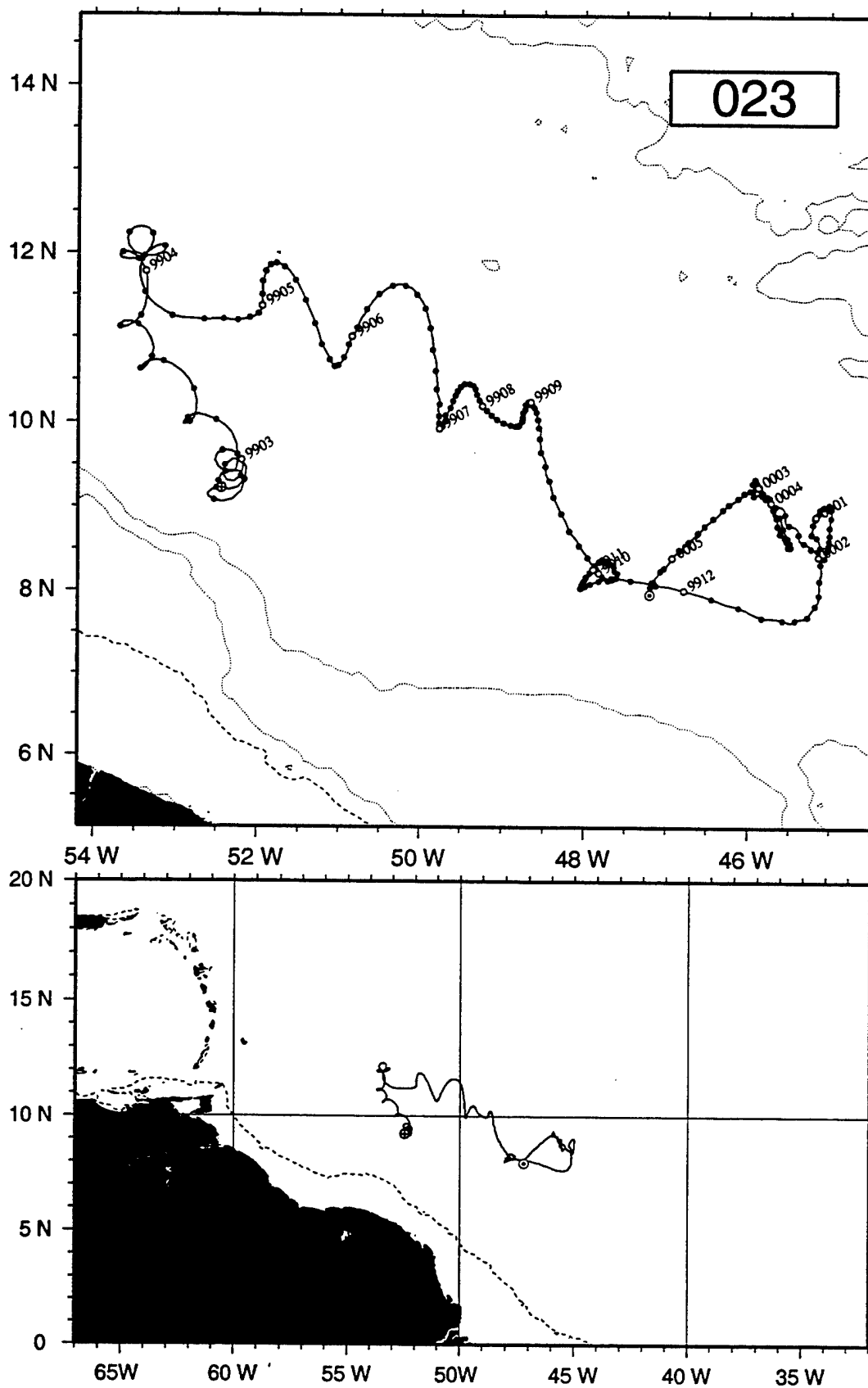




br022

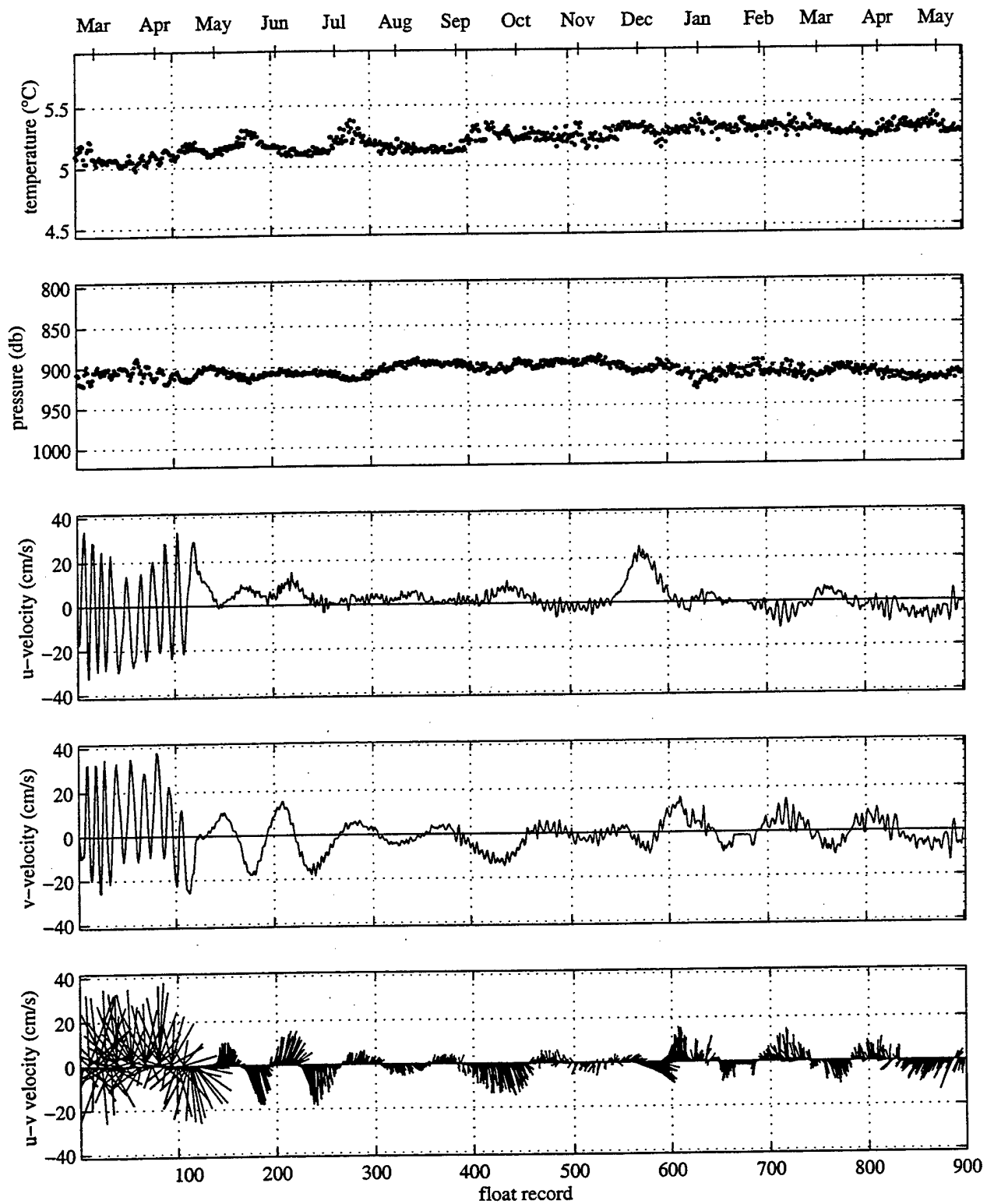
2000

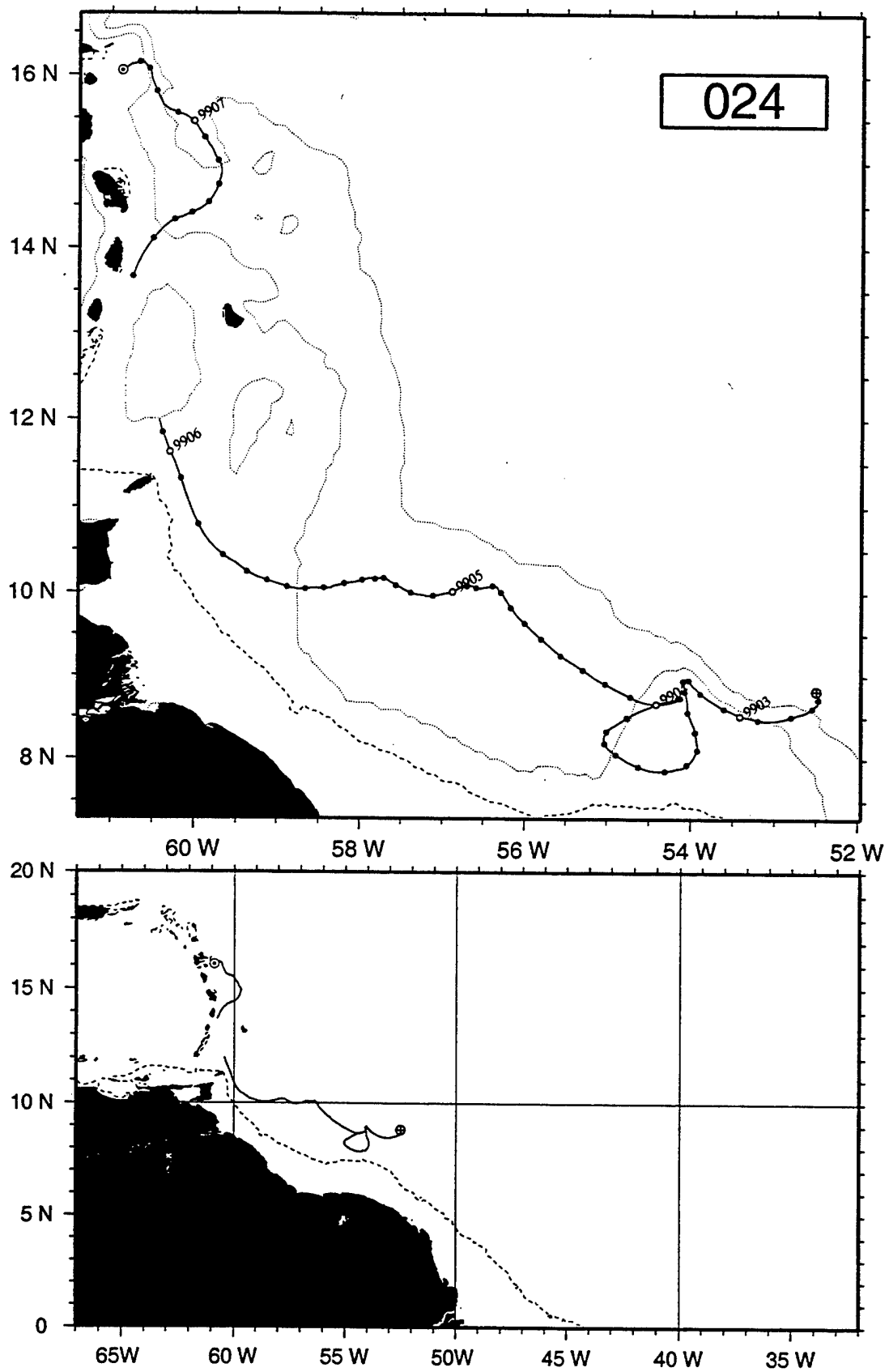




br023

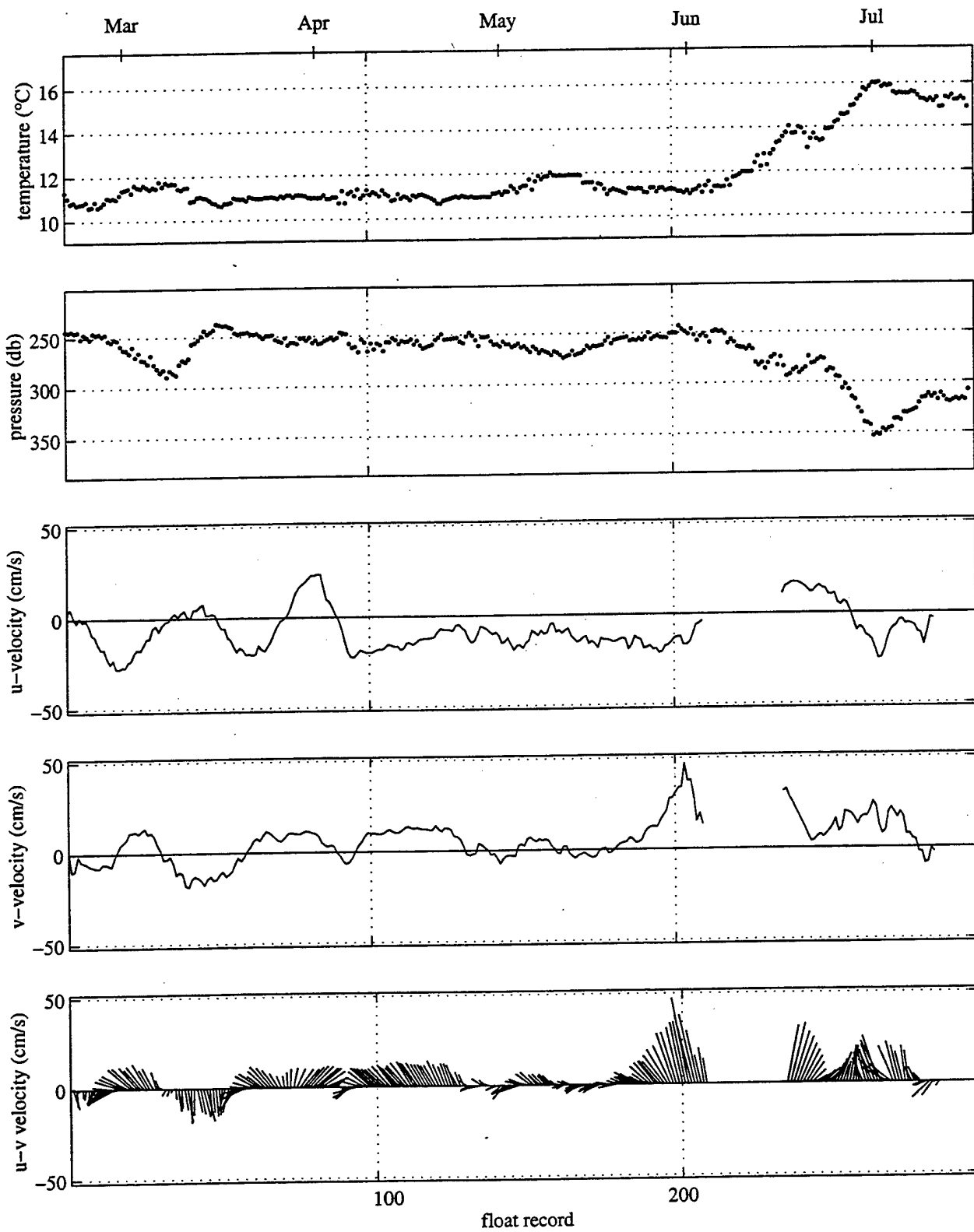
2000

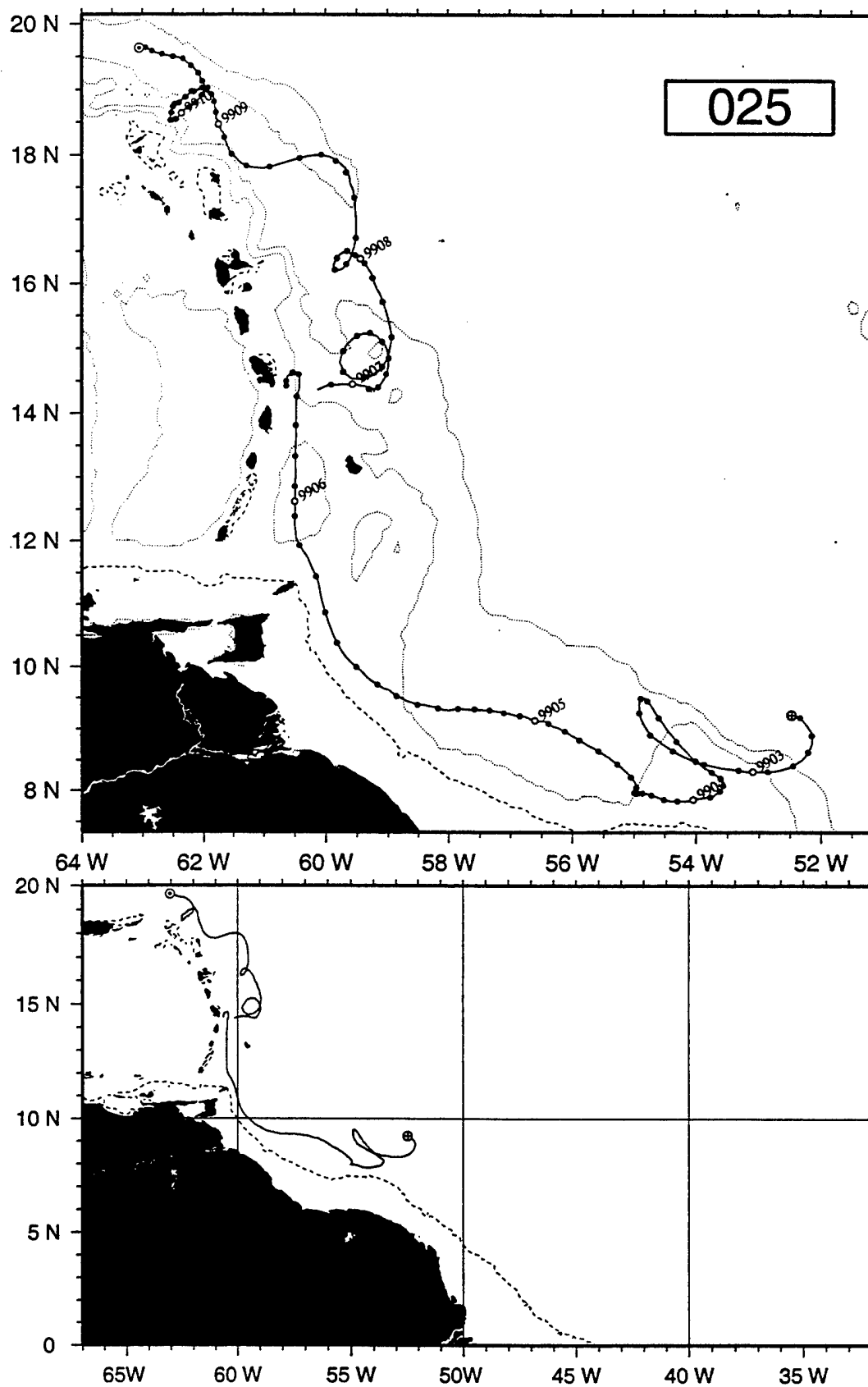




br024

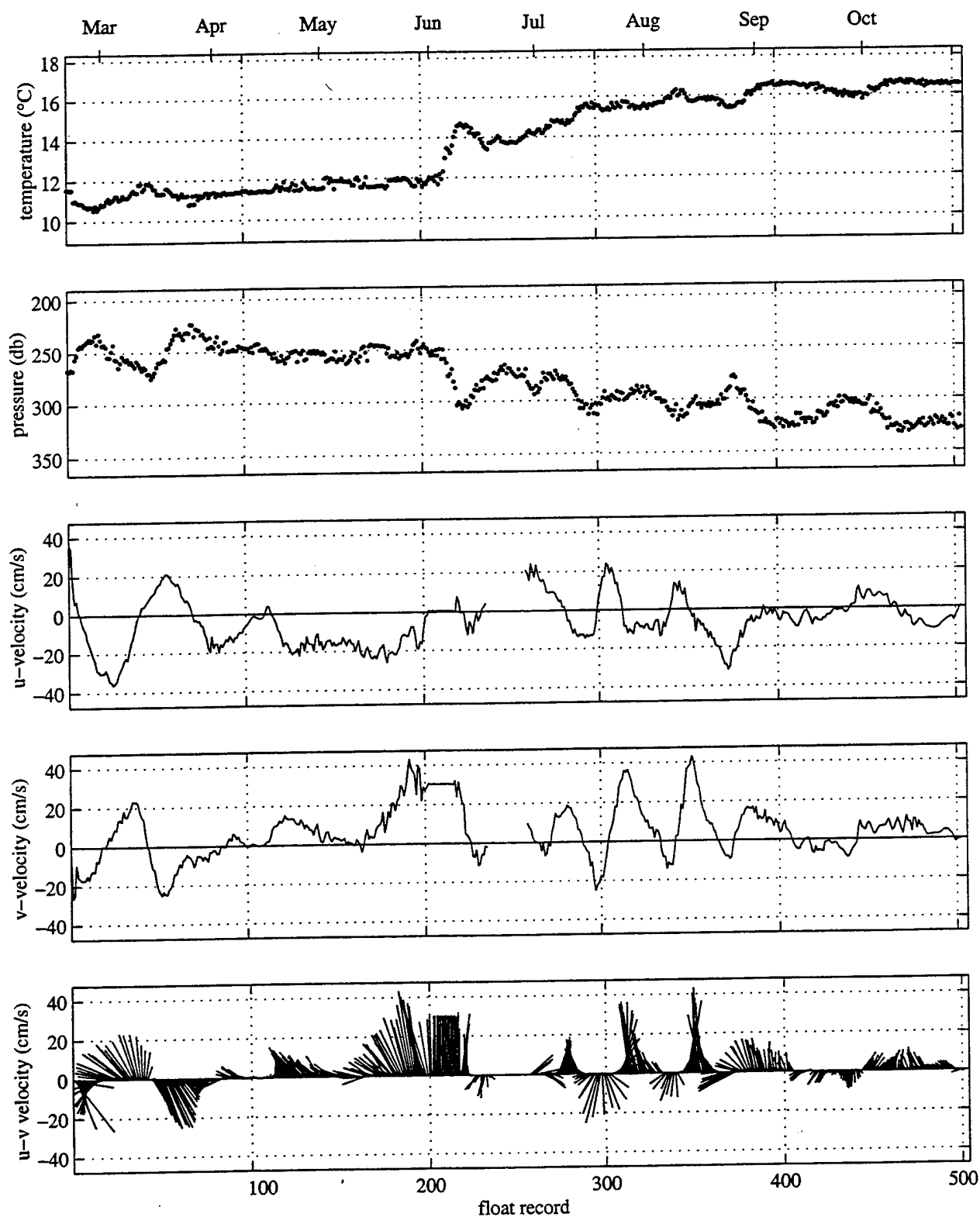
1999

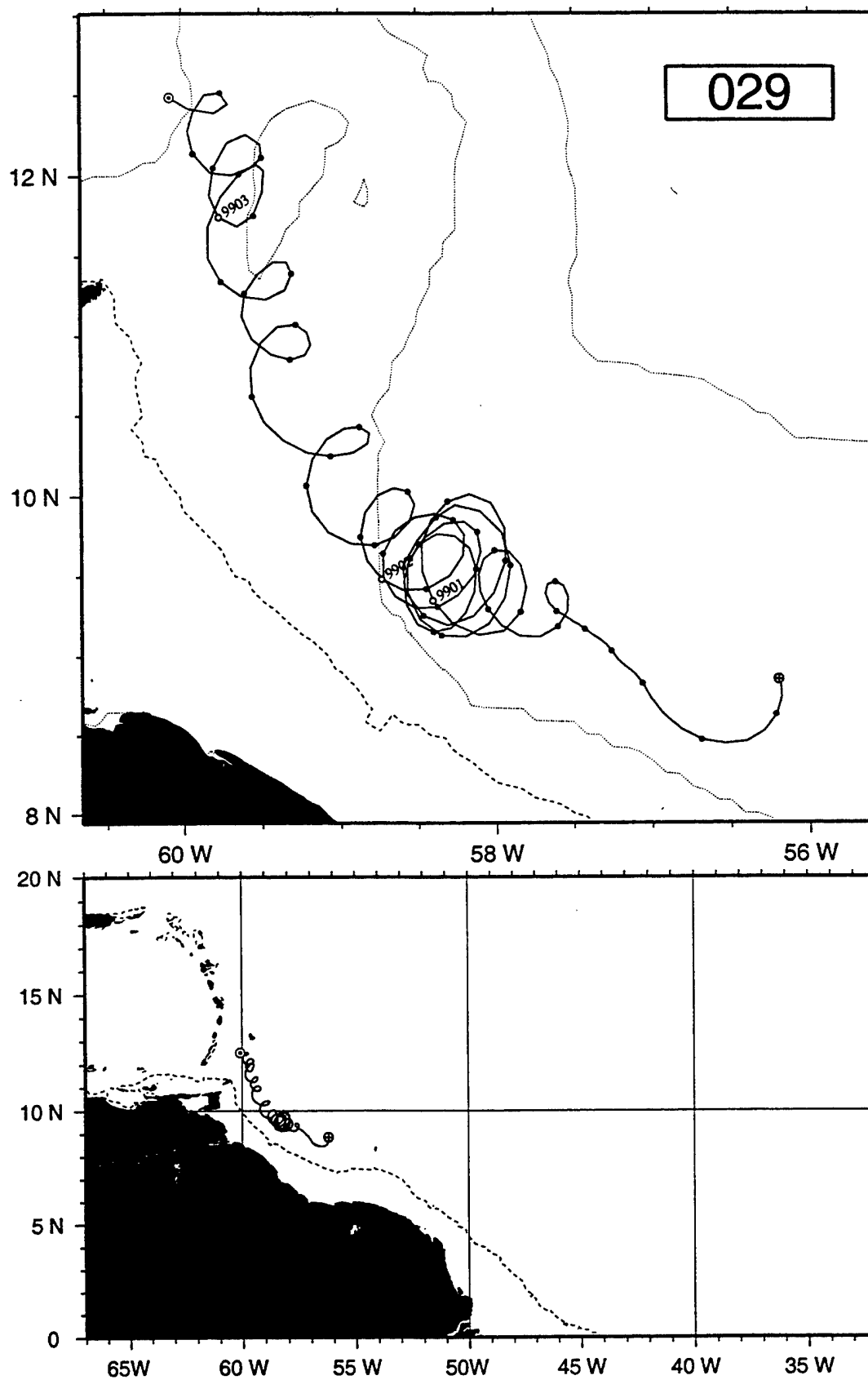




br025

1999







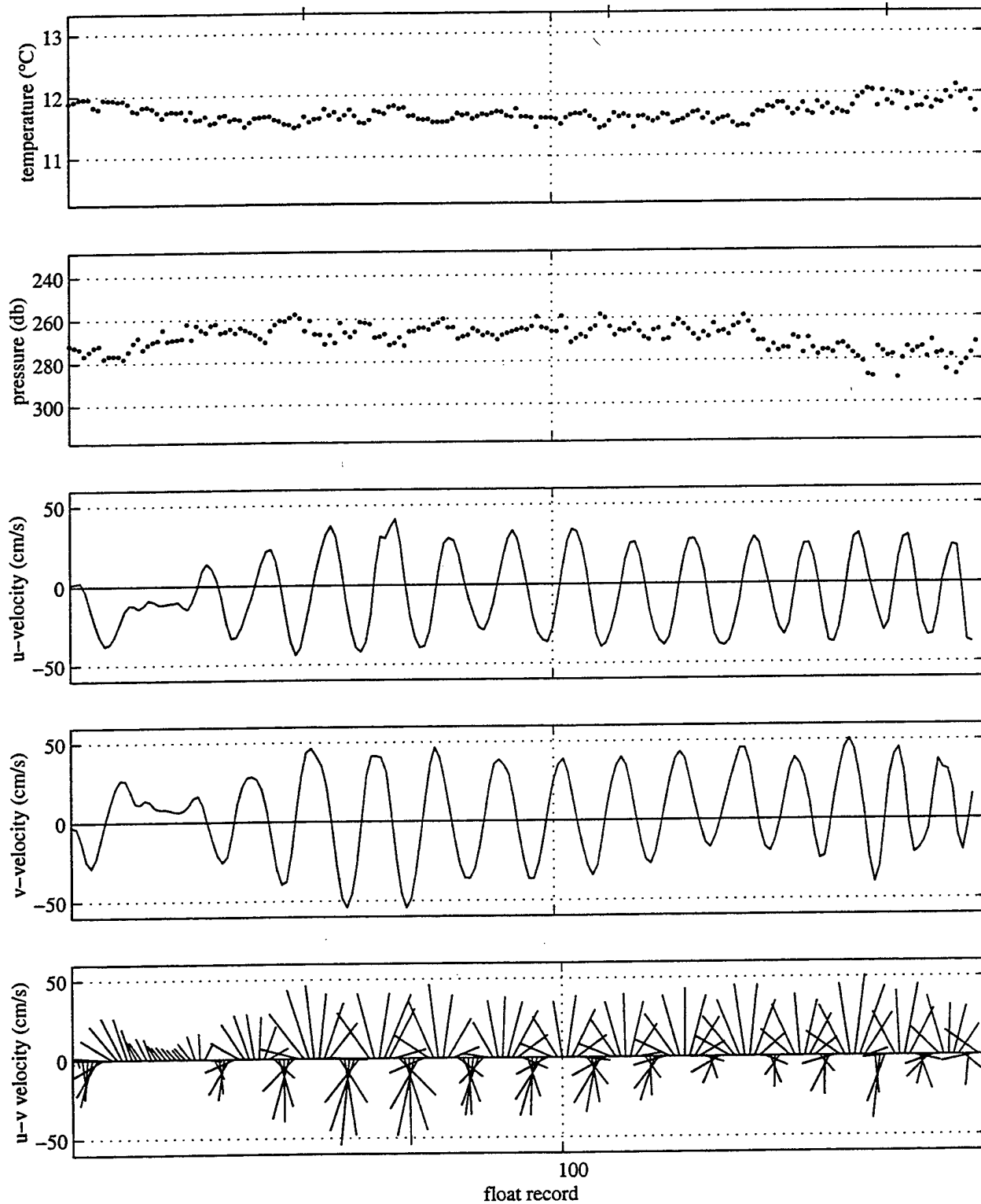
br029

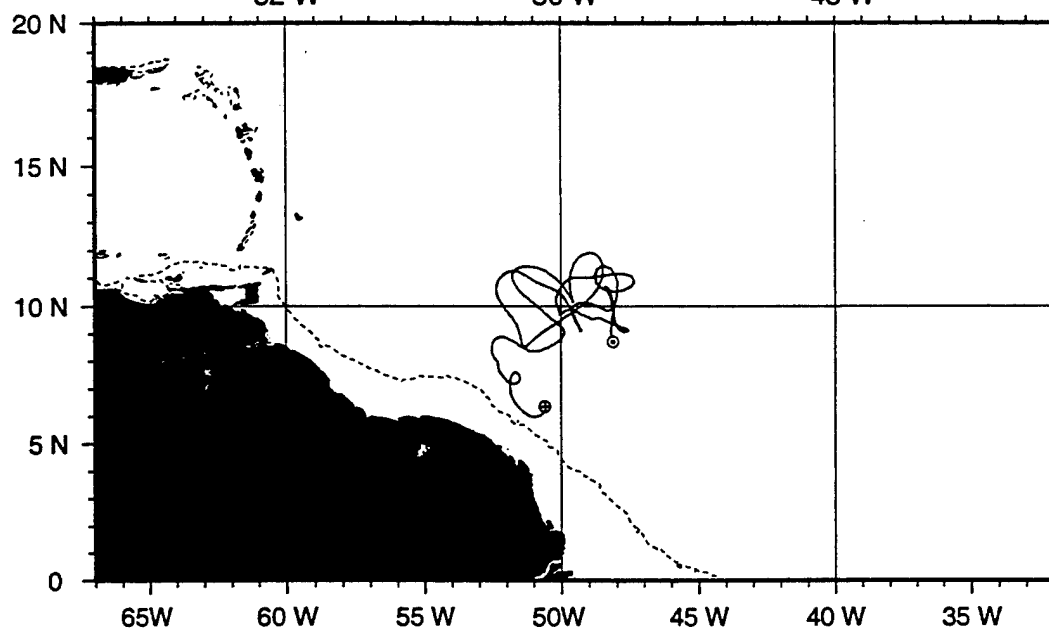
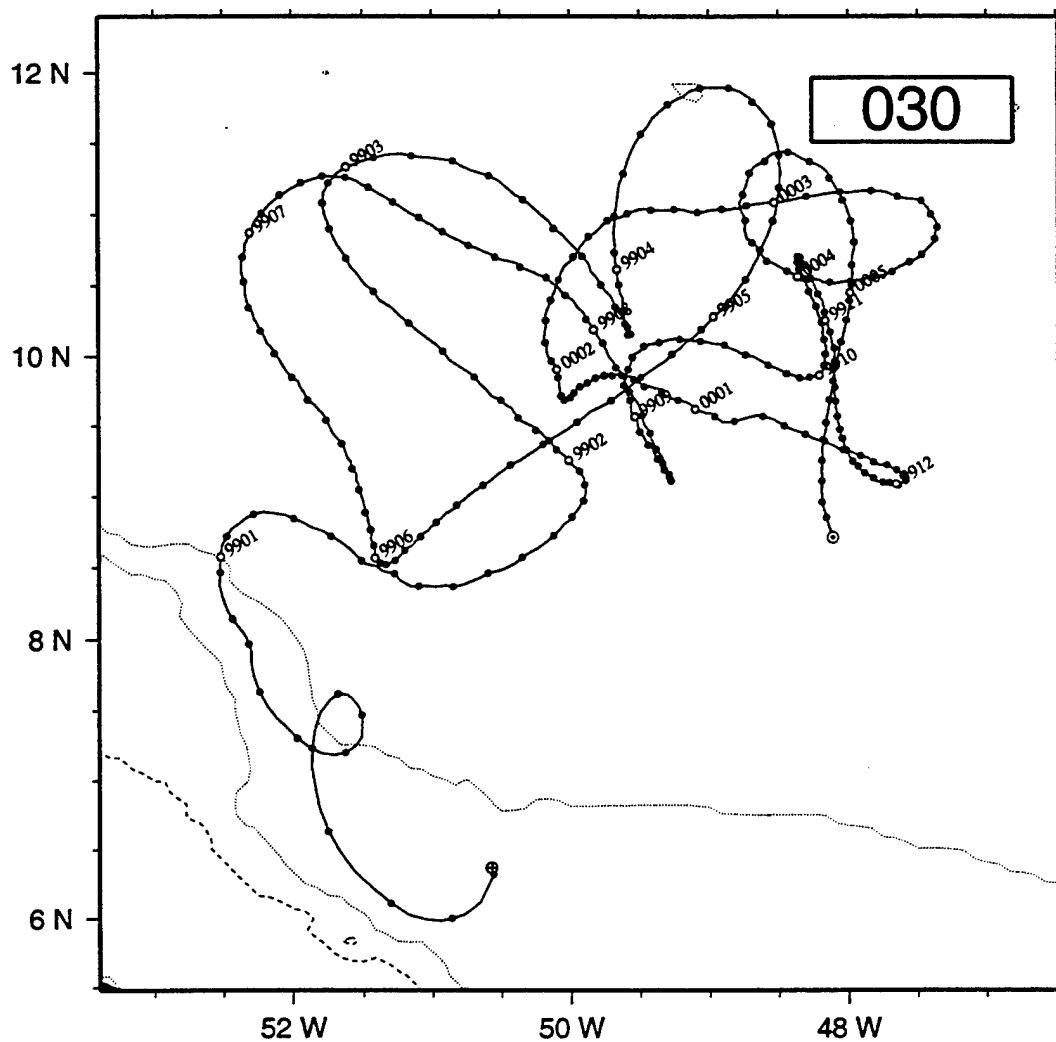
1999

Jan

Feb

Mar

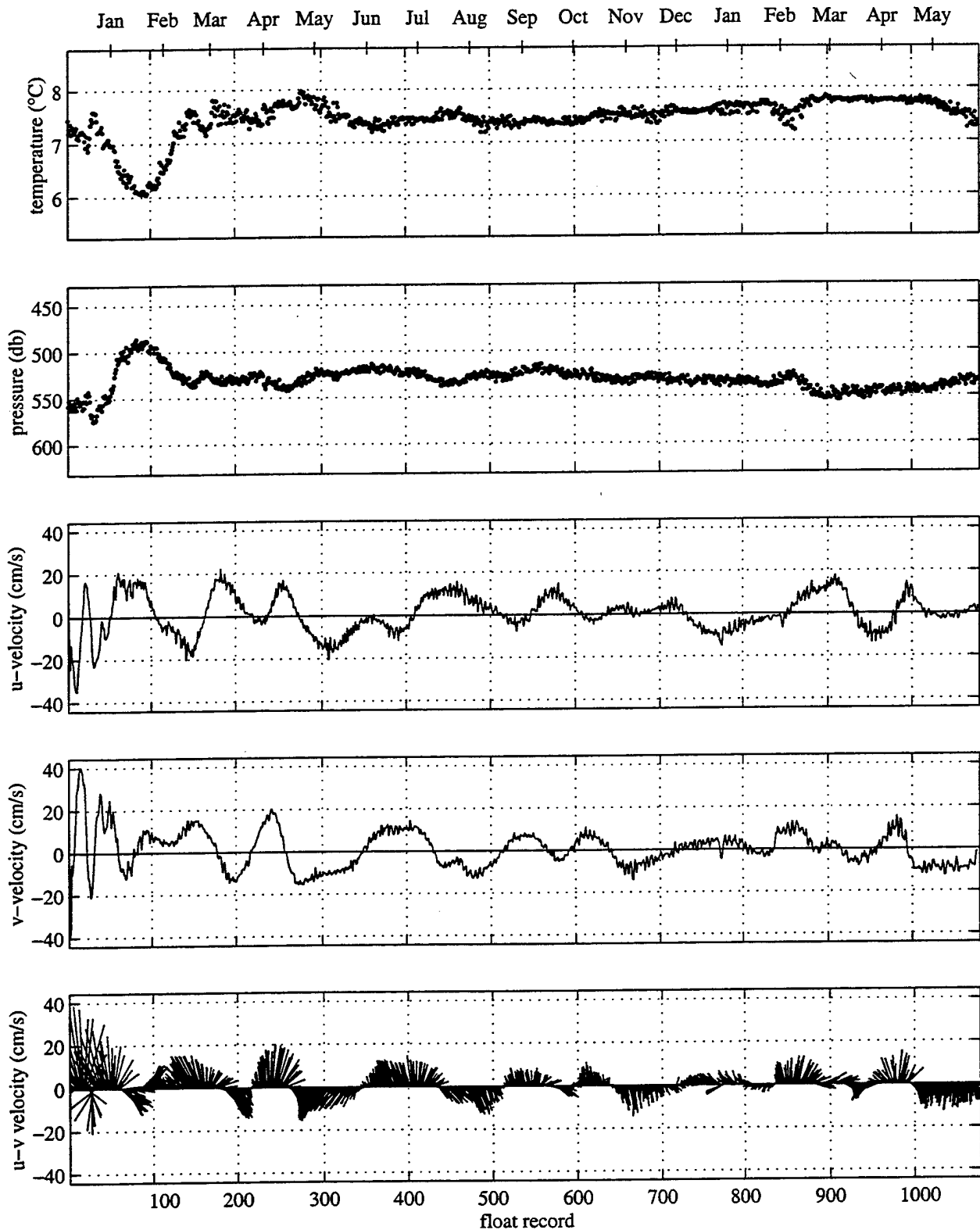


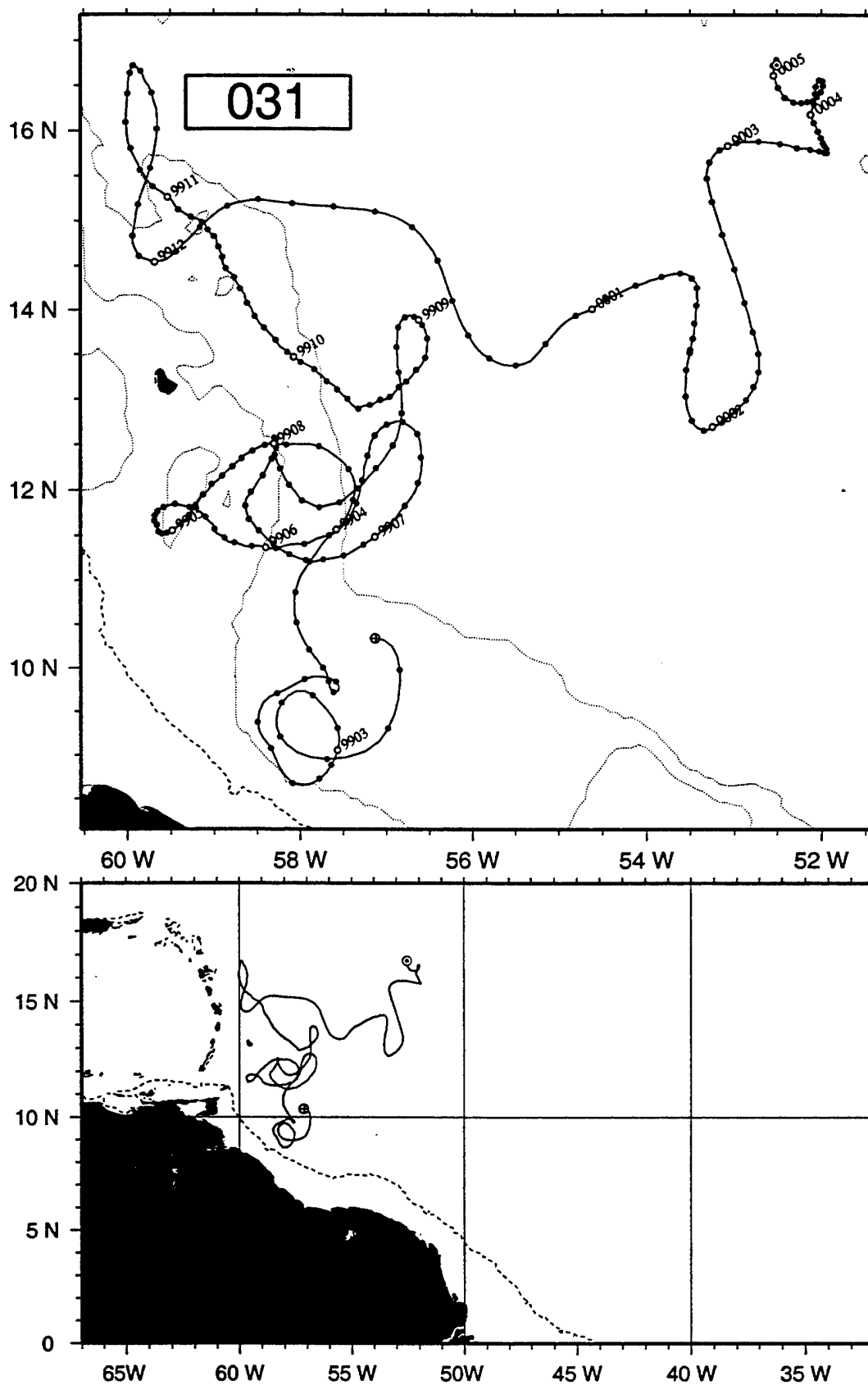


# br030

1999

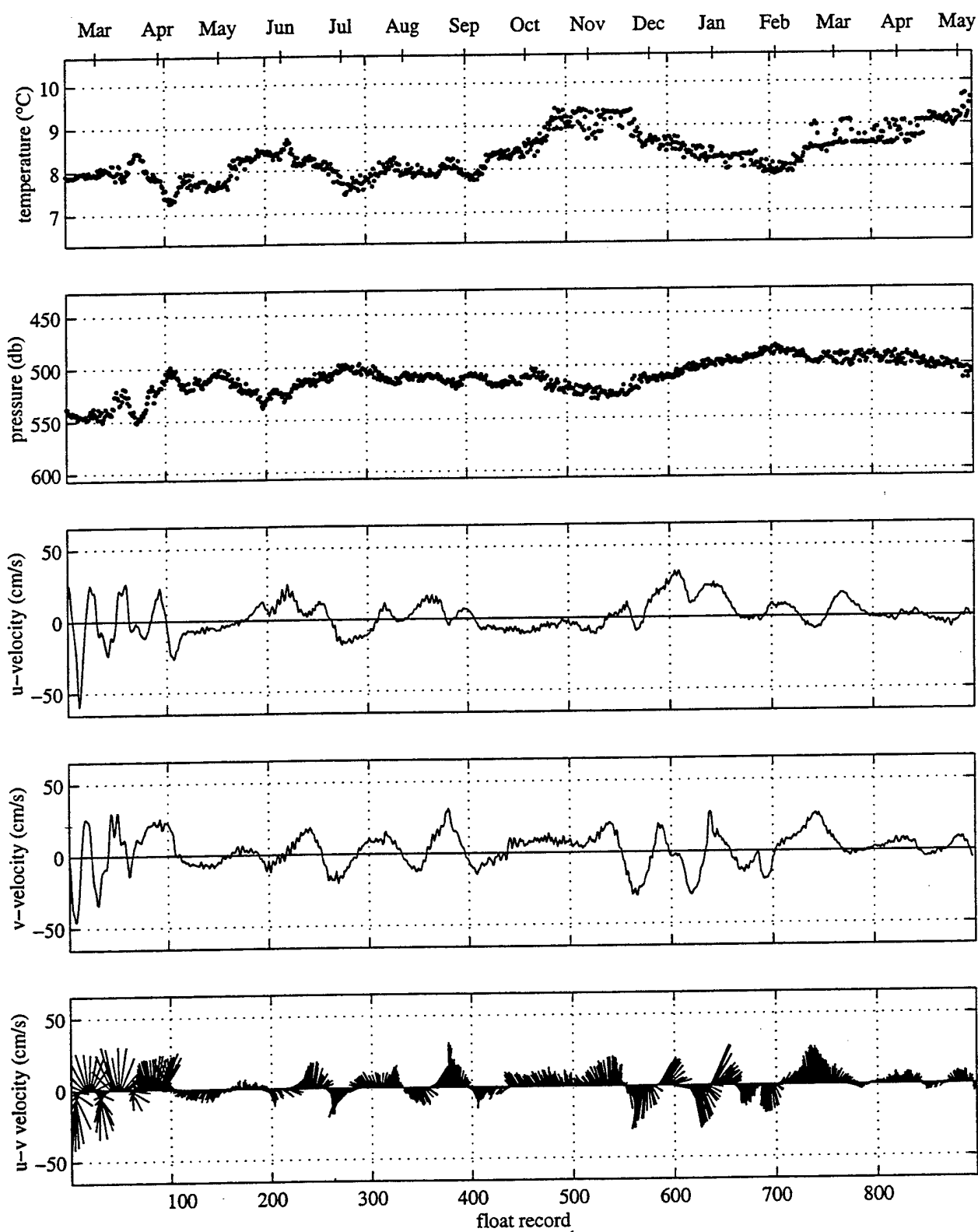
2000

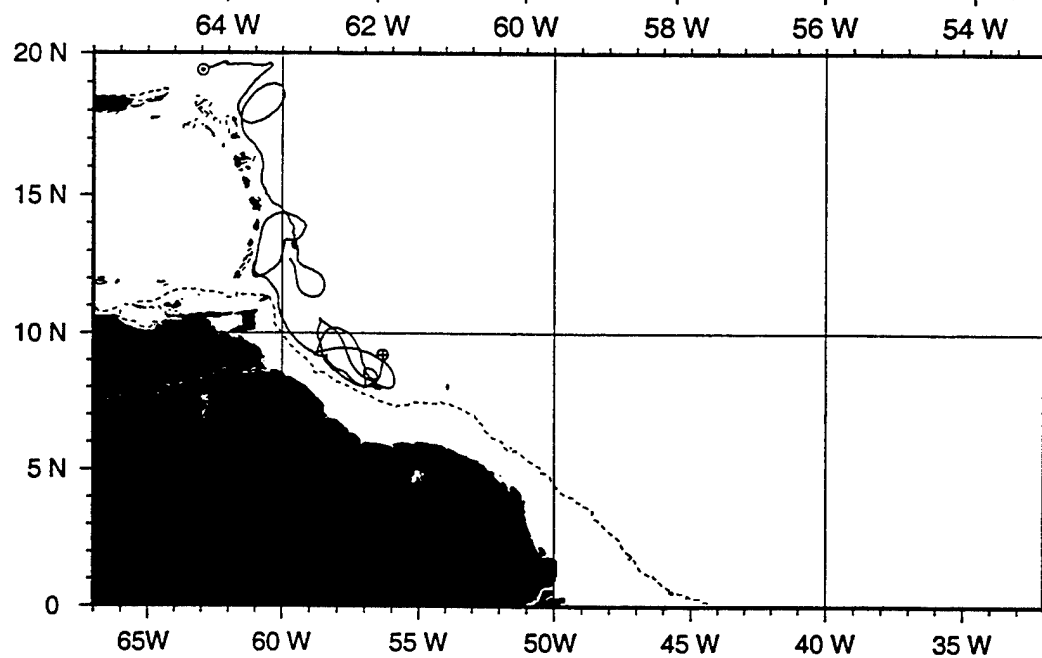
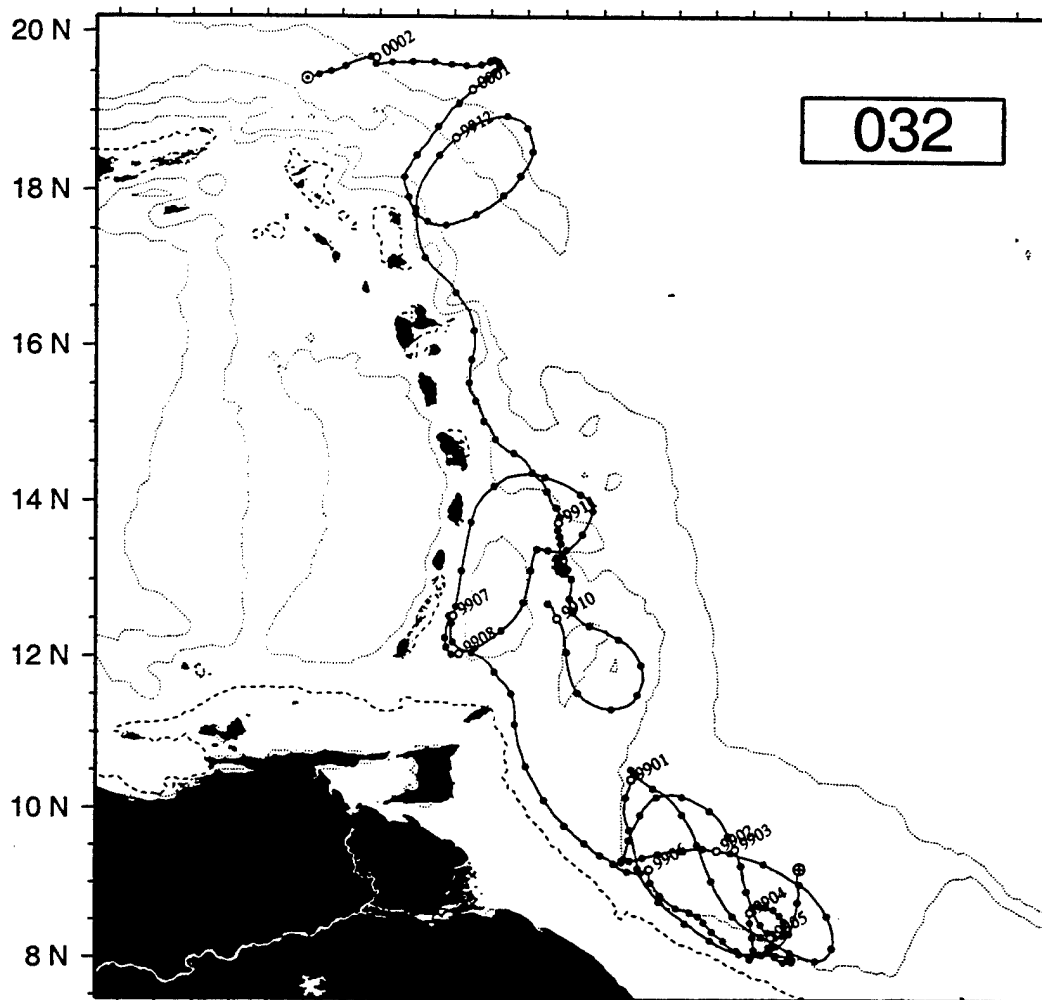




br031

2000

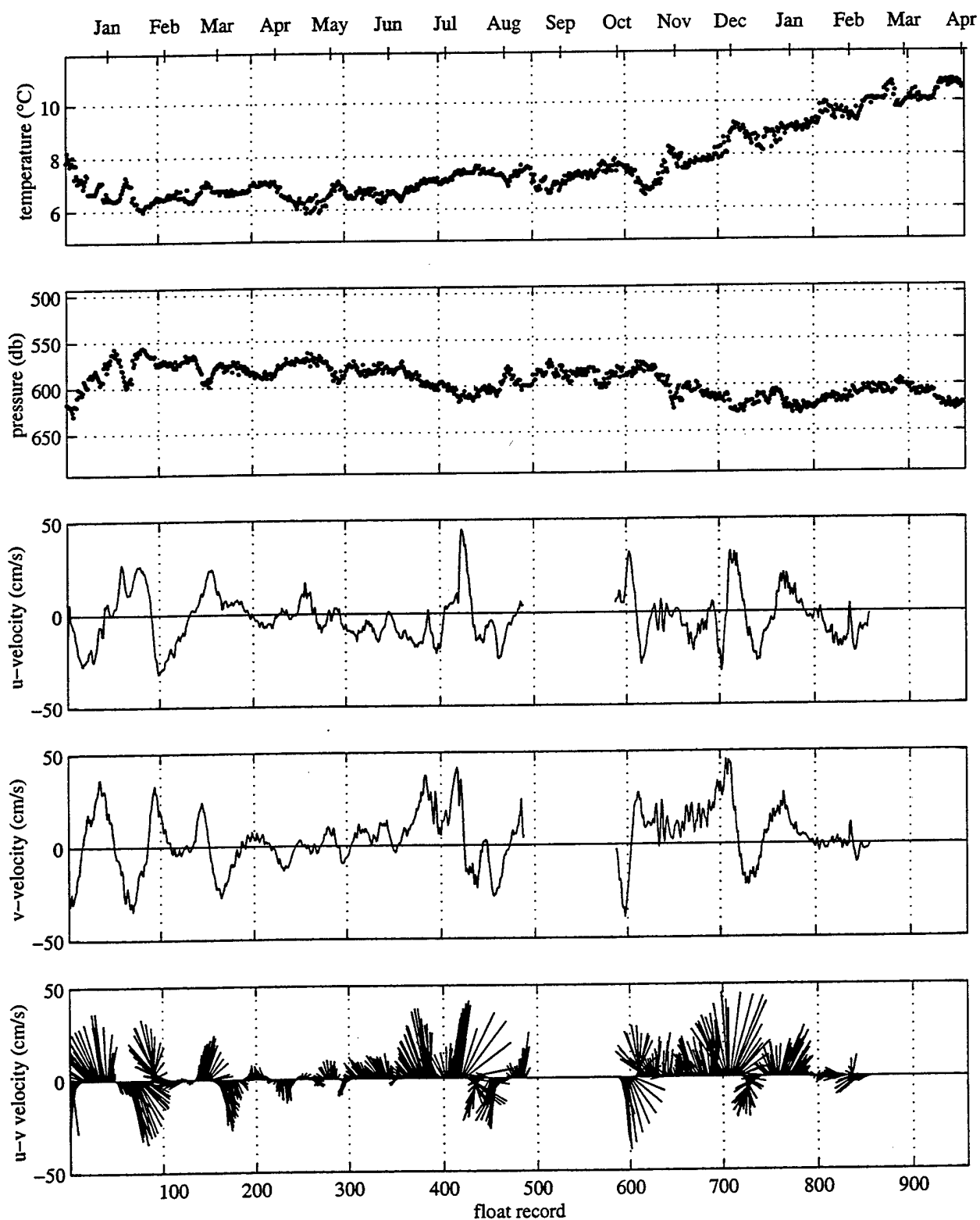


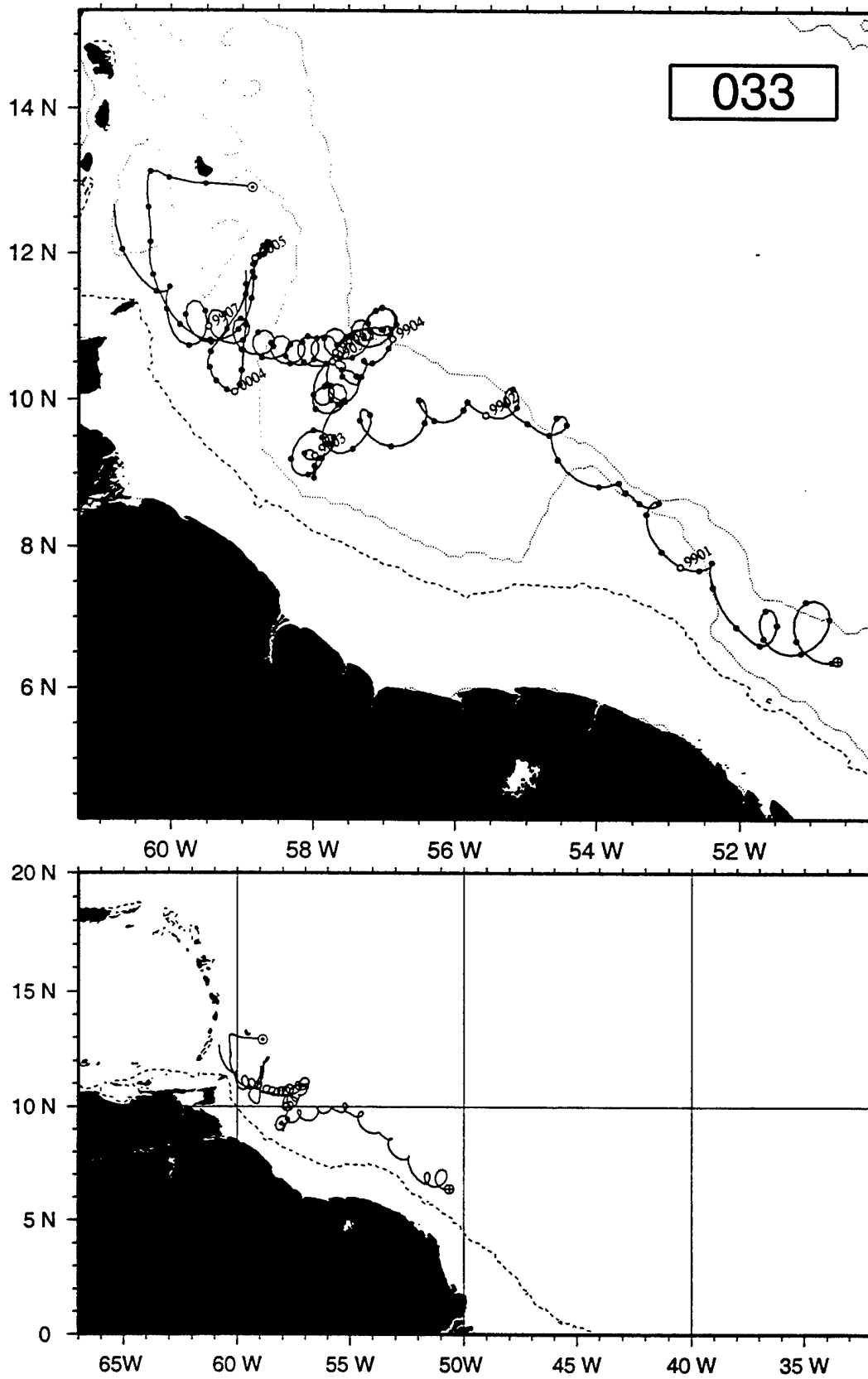


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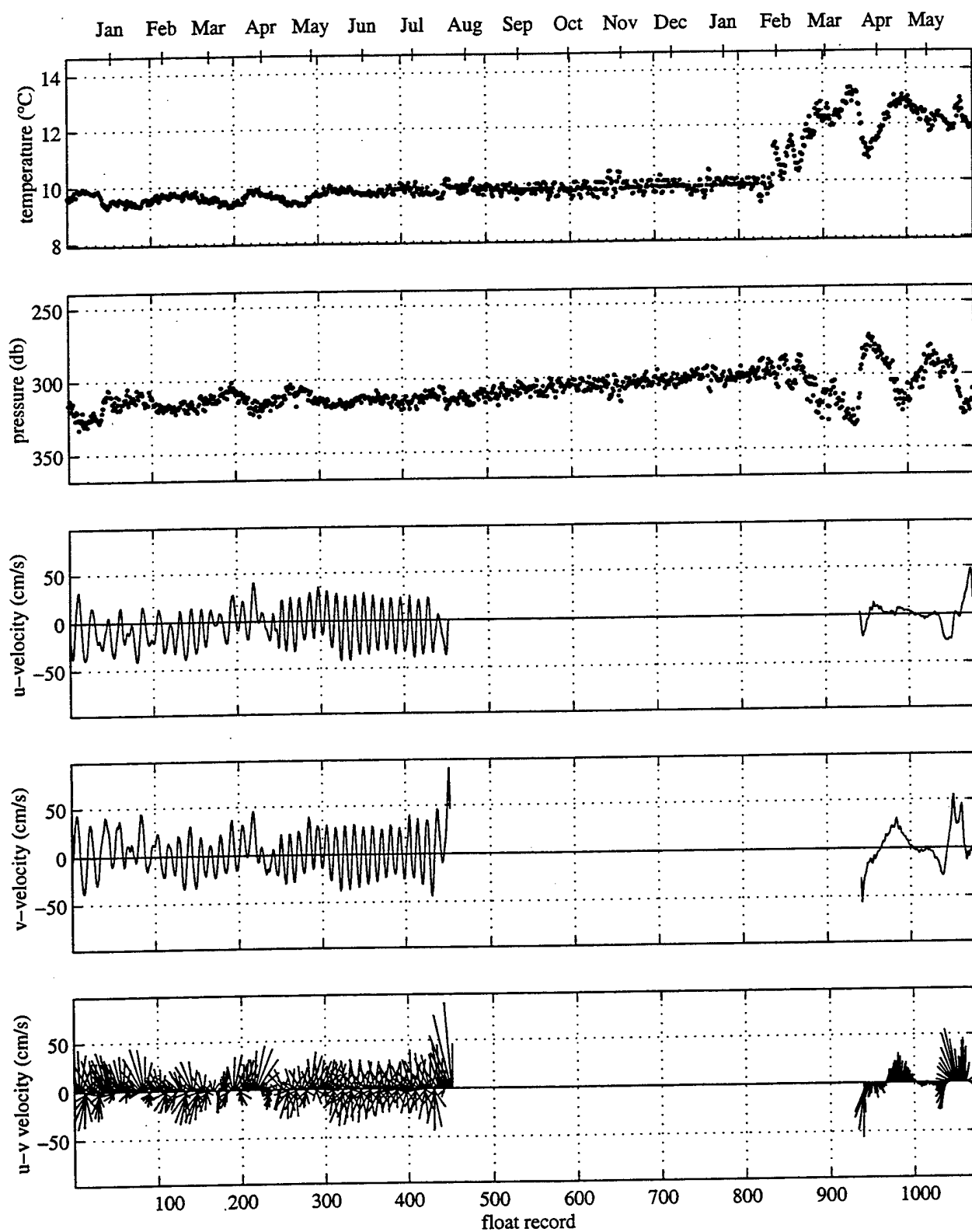


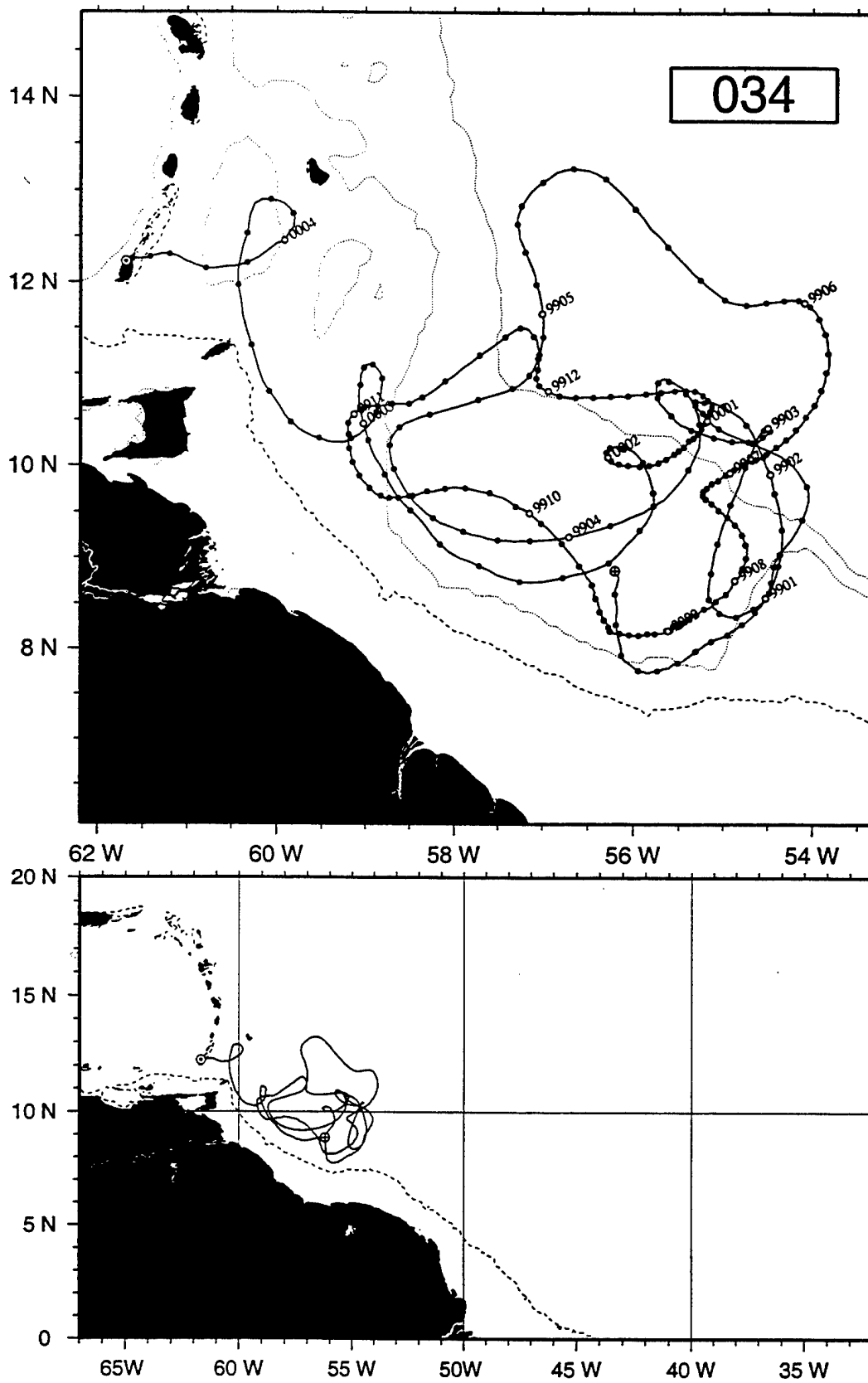


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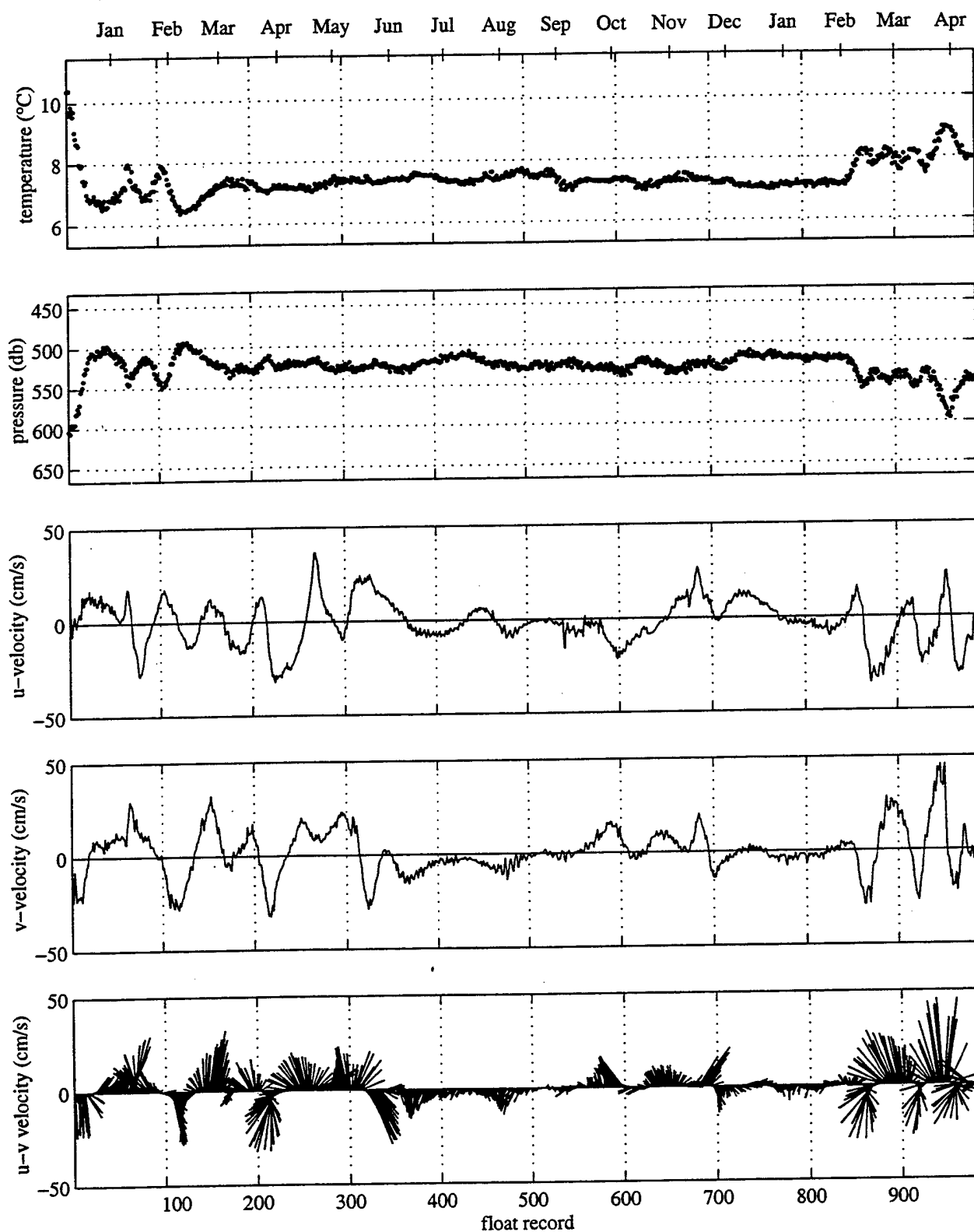


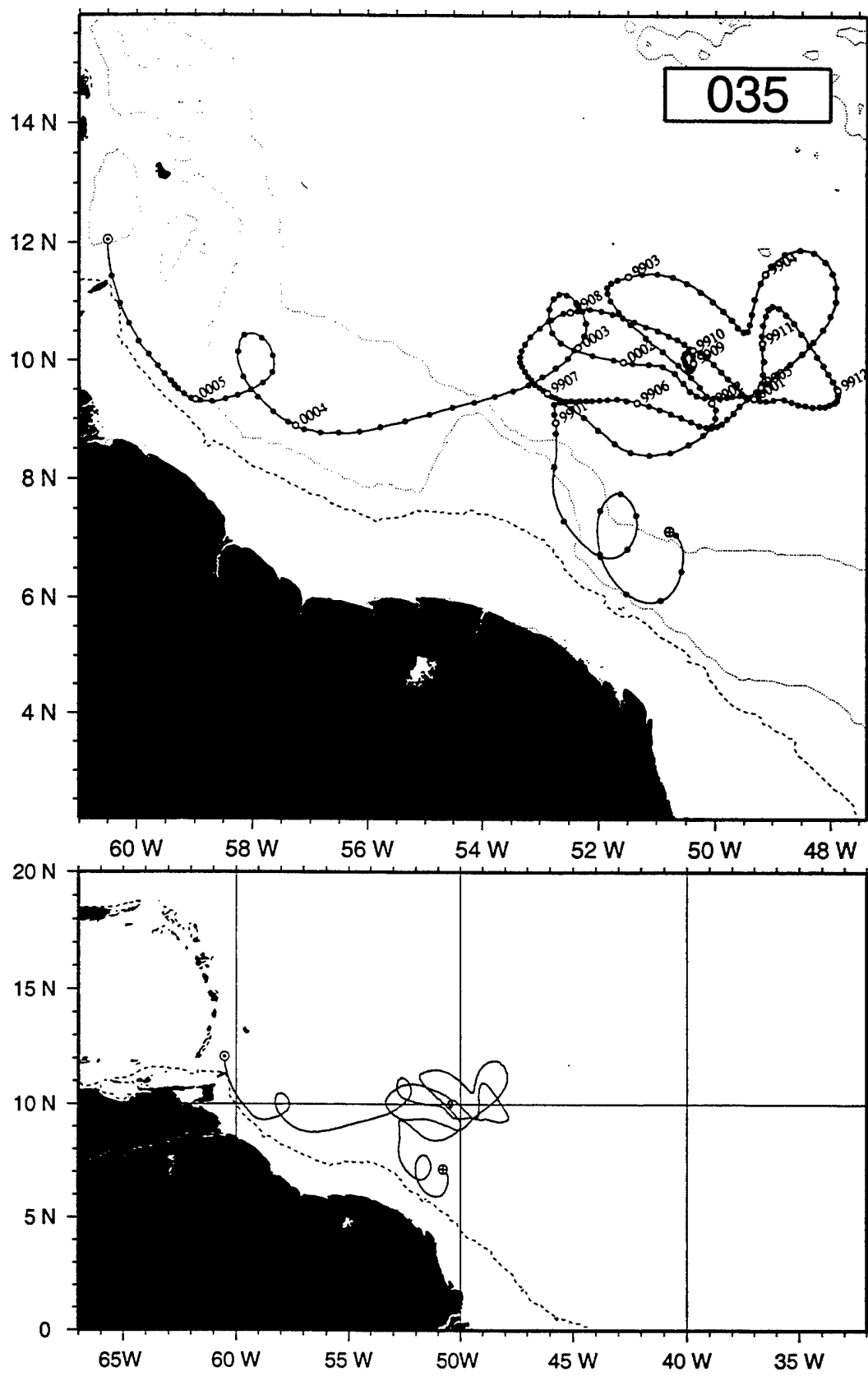


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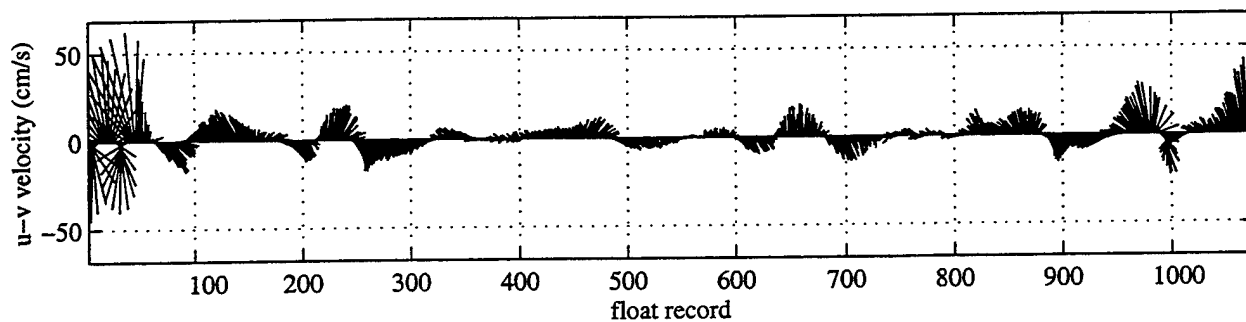
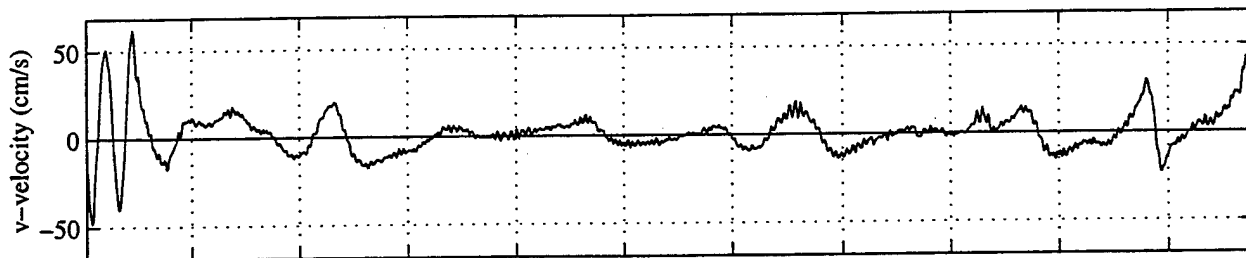
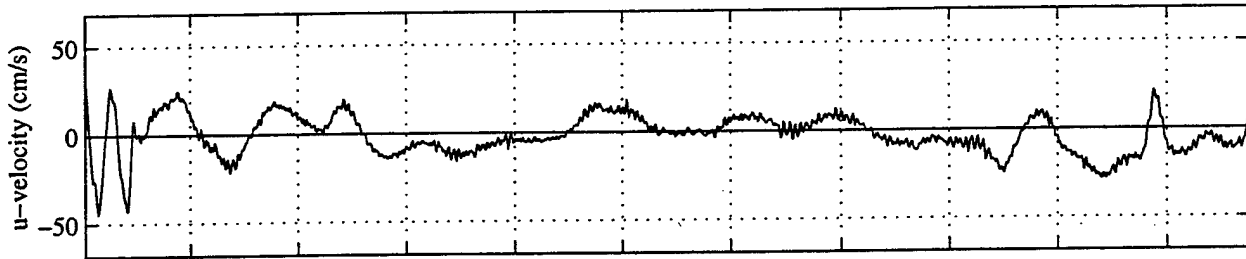
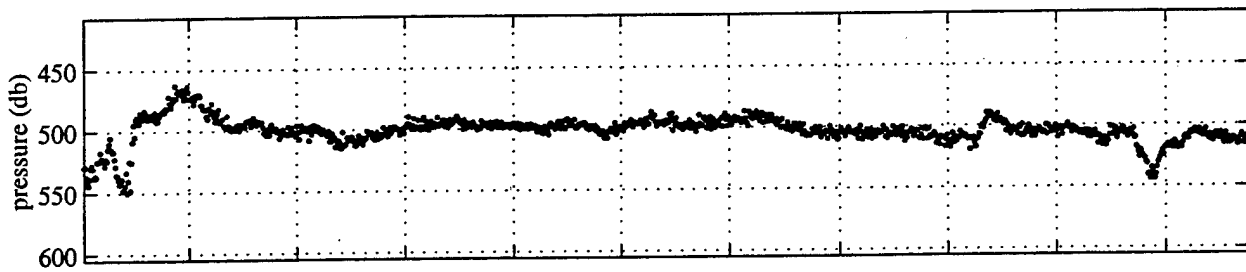
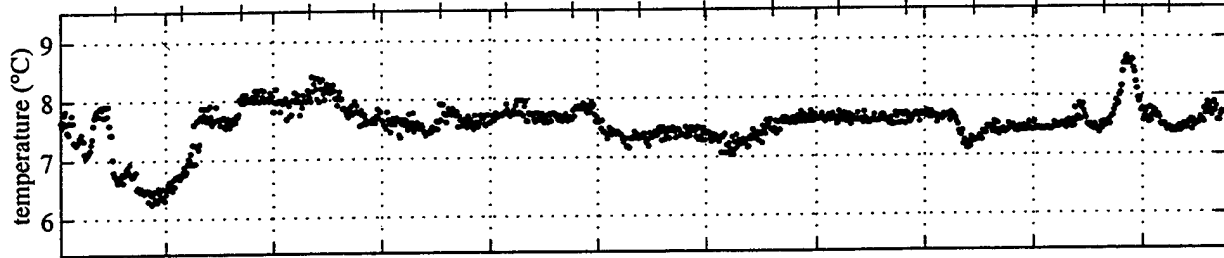


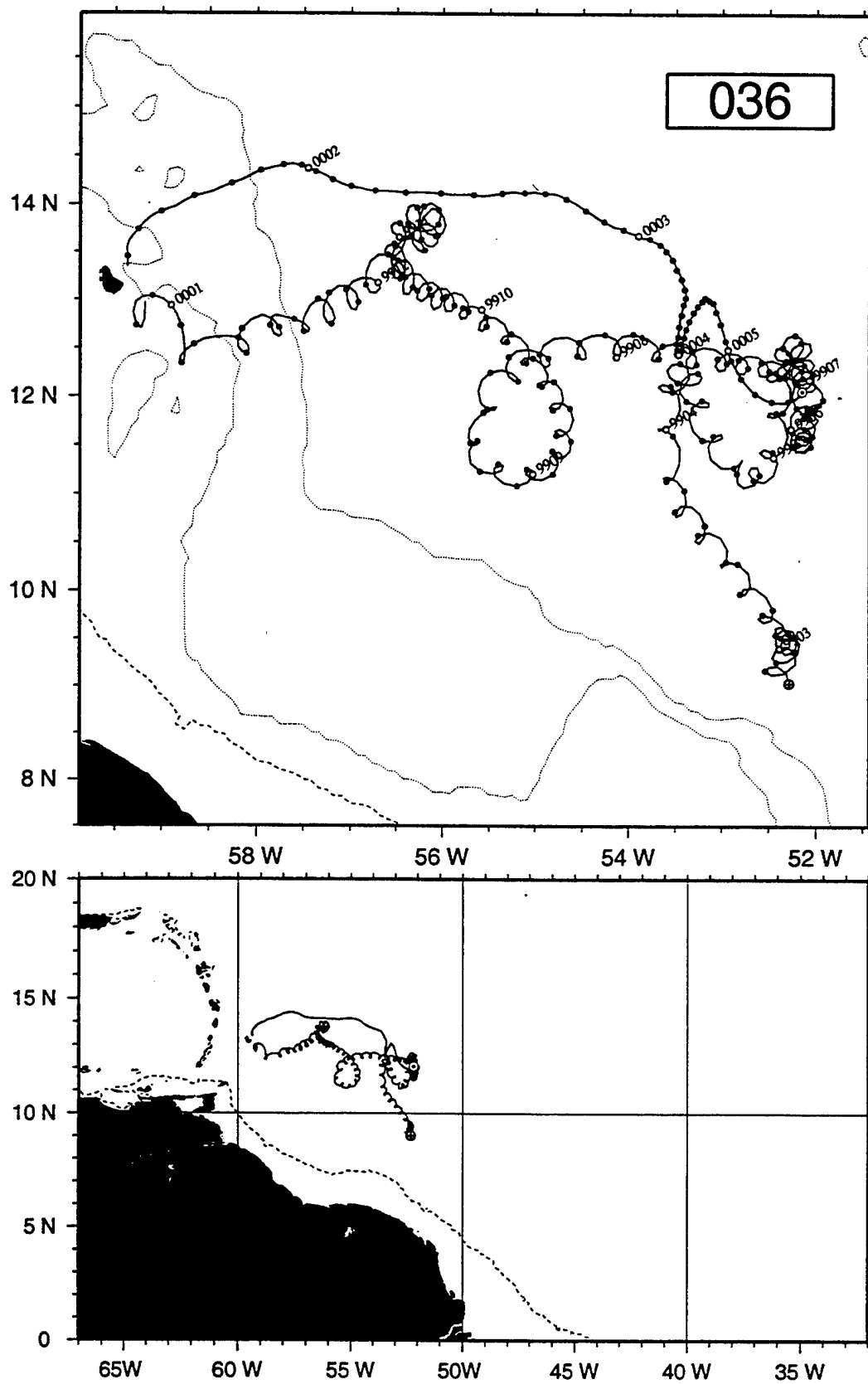
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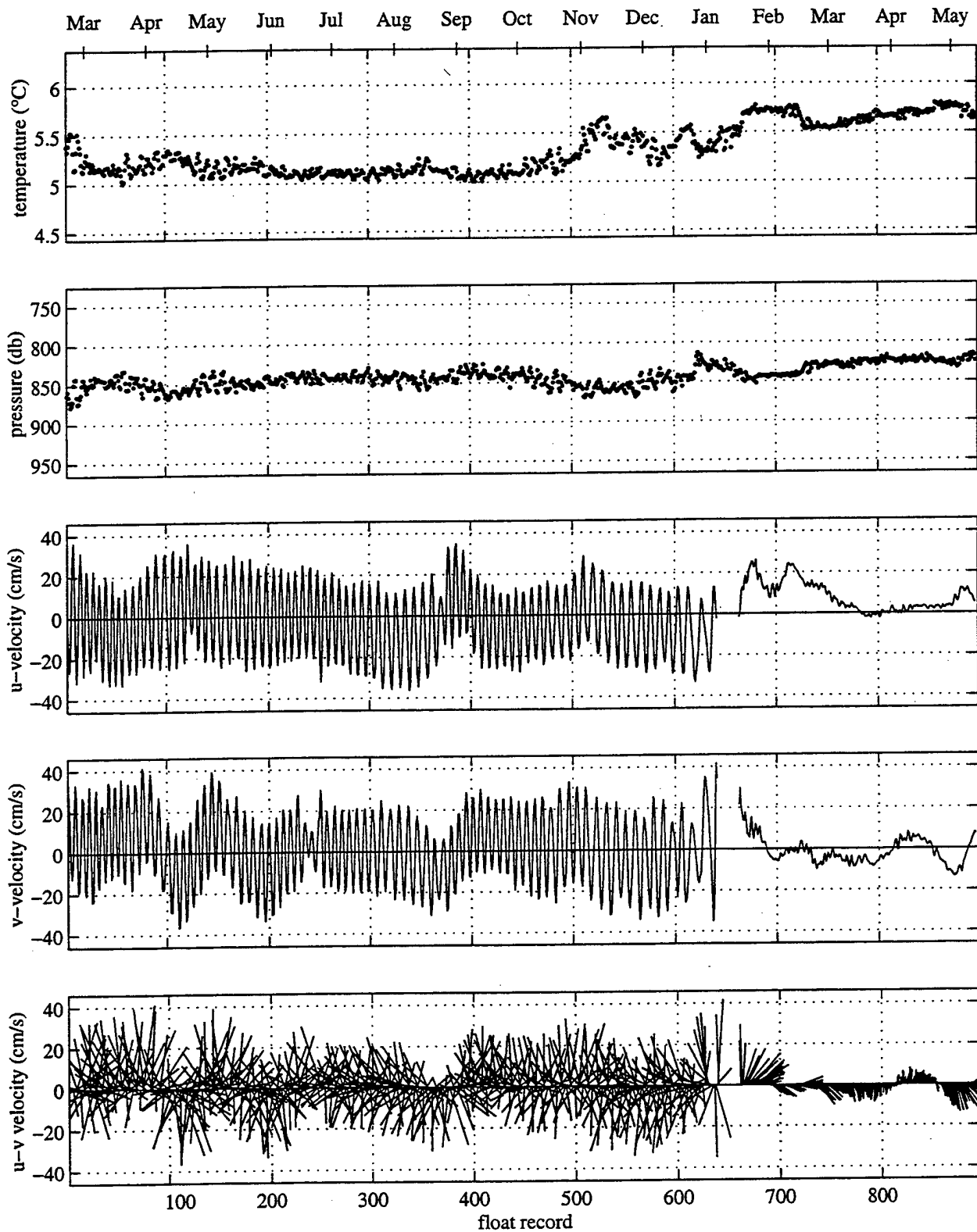
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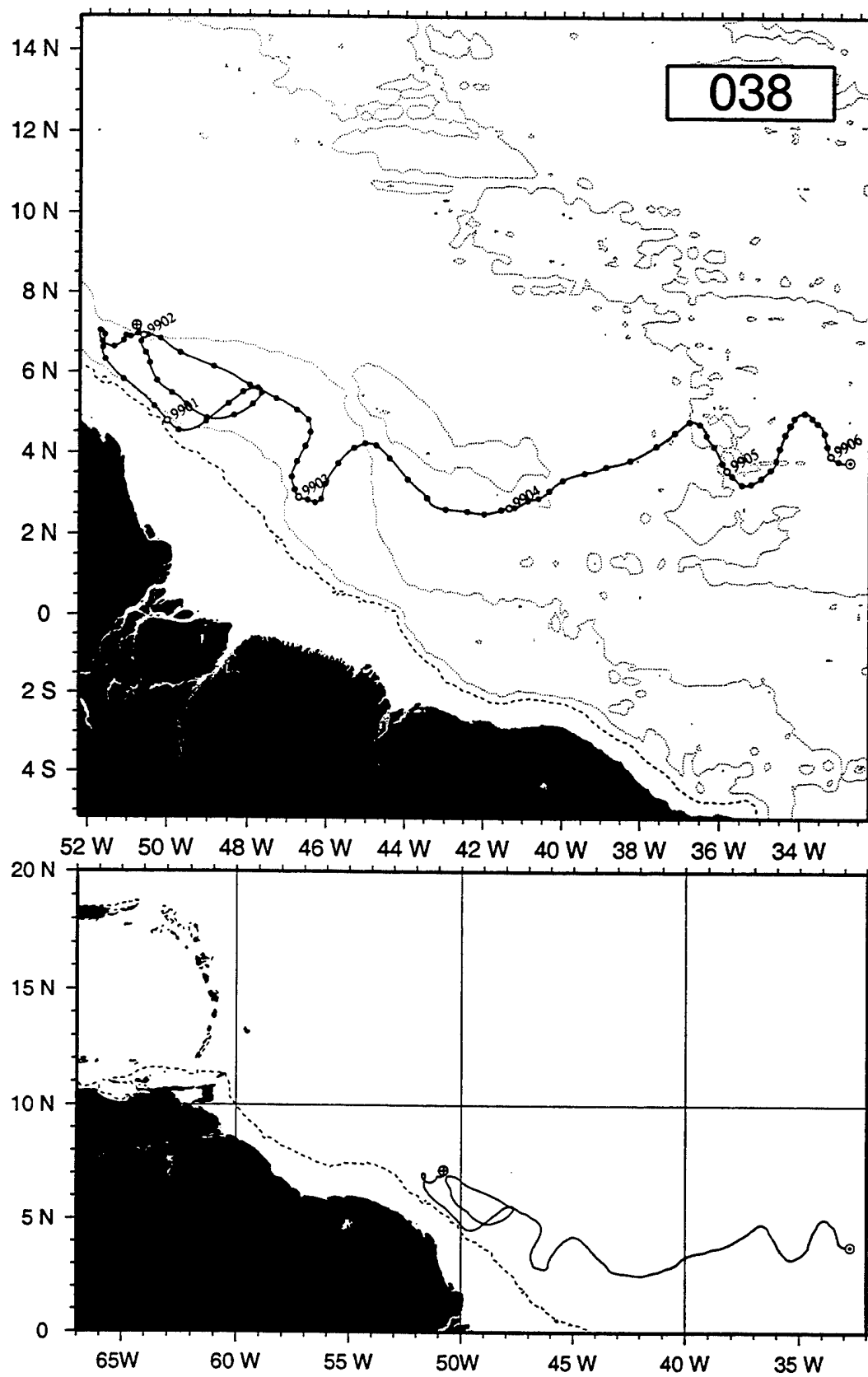




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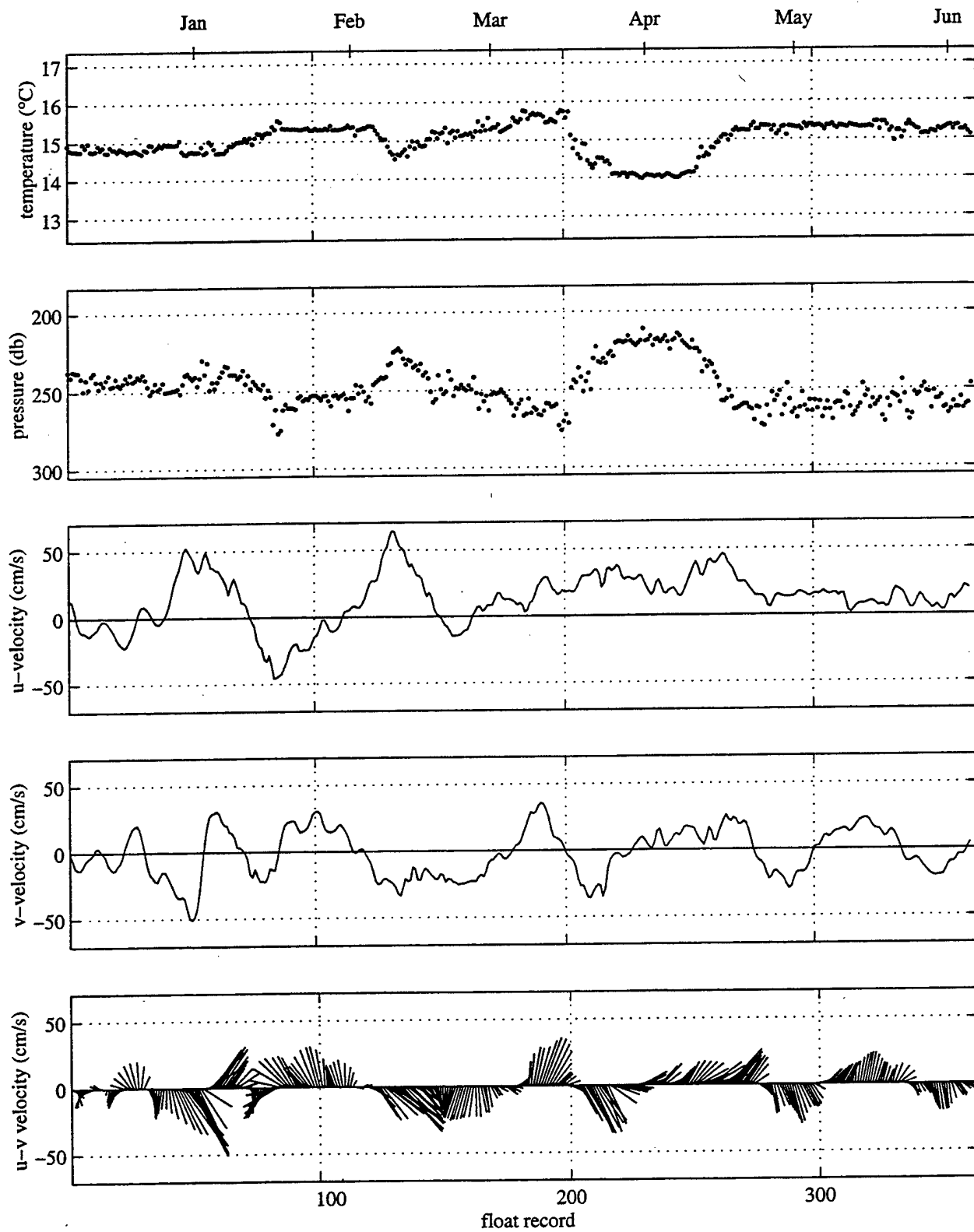


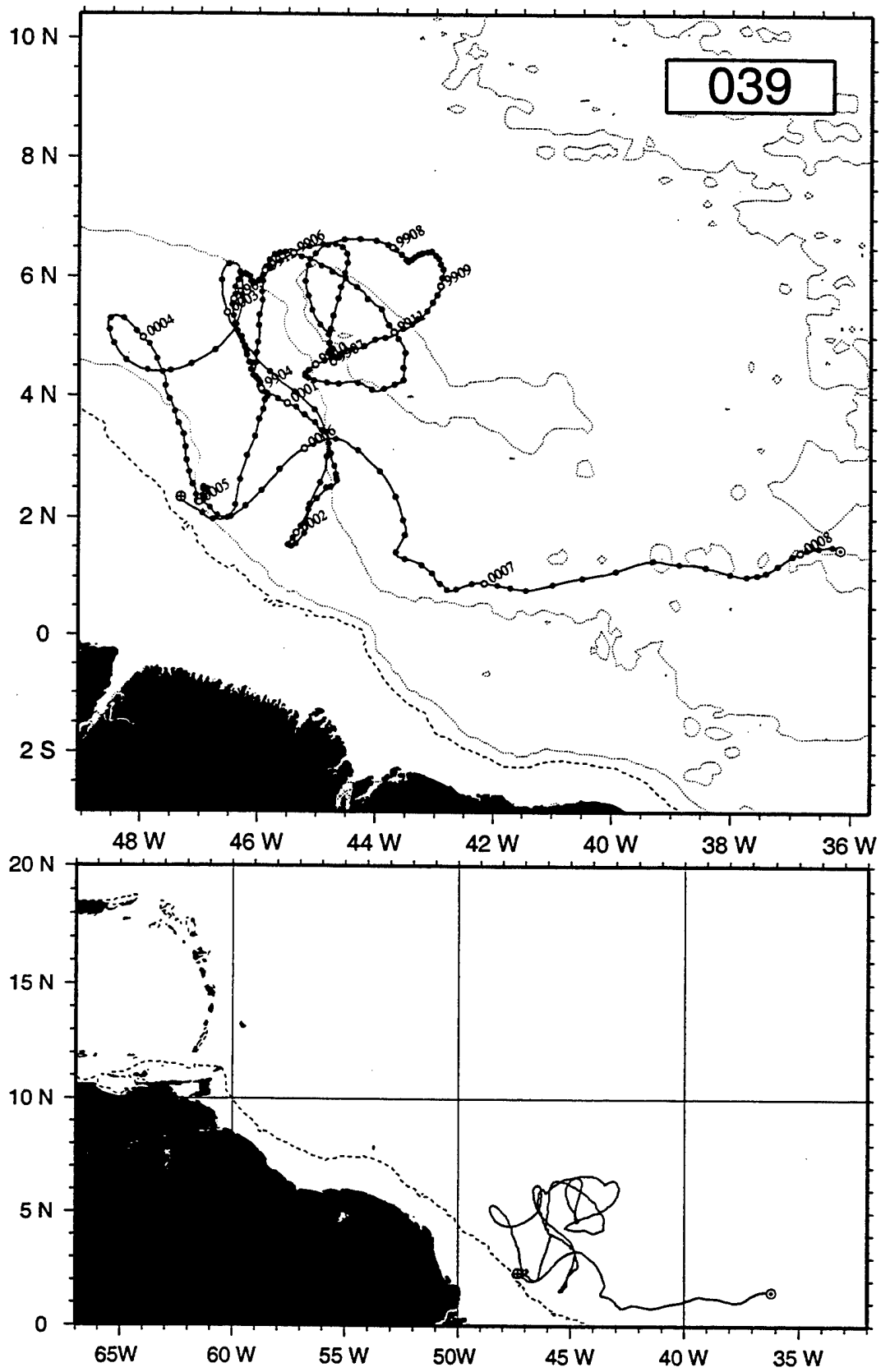




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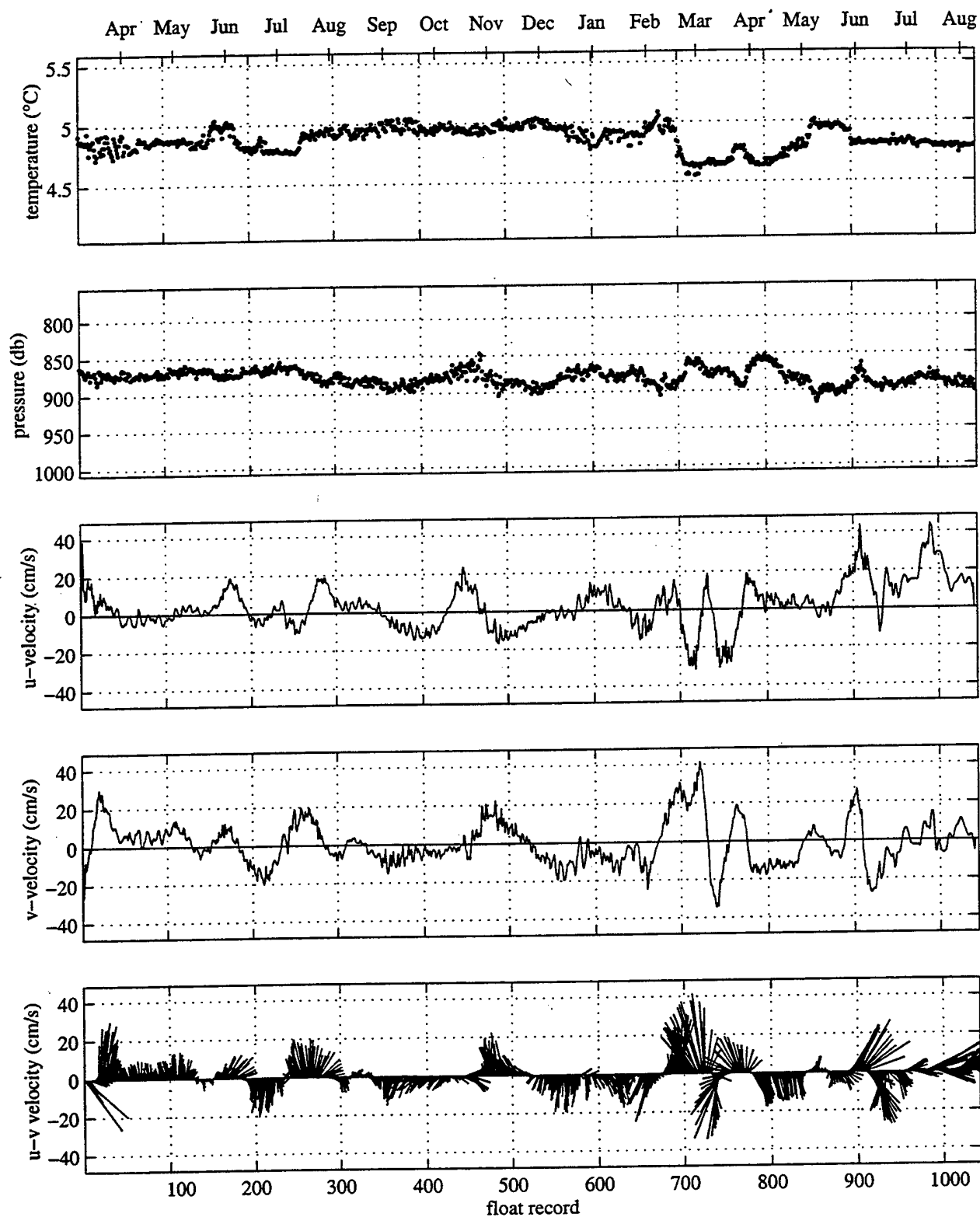
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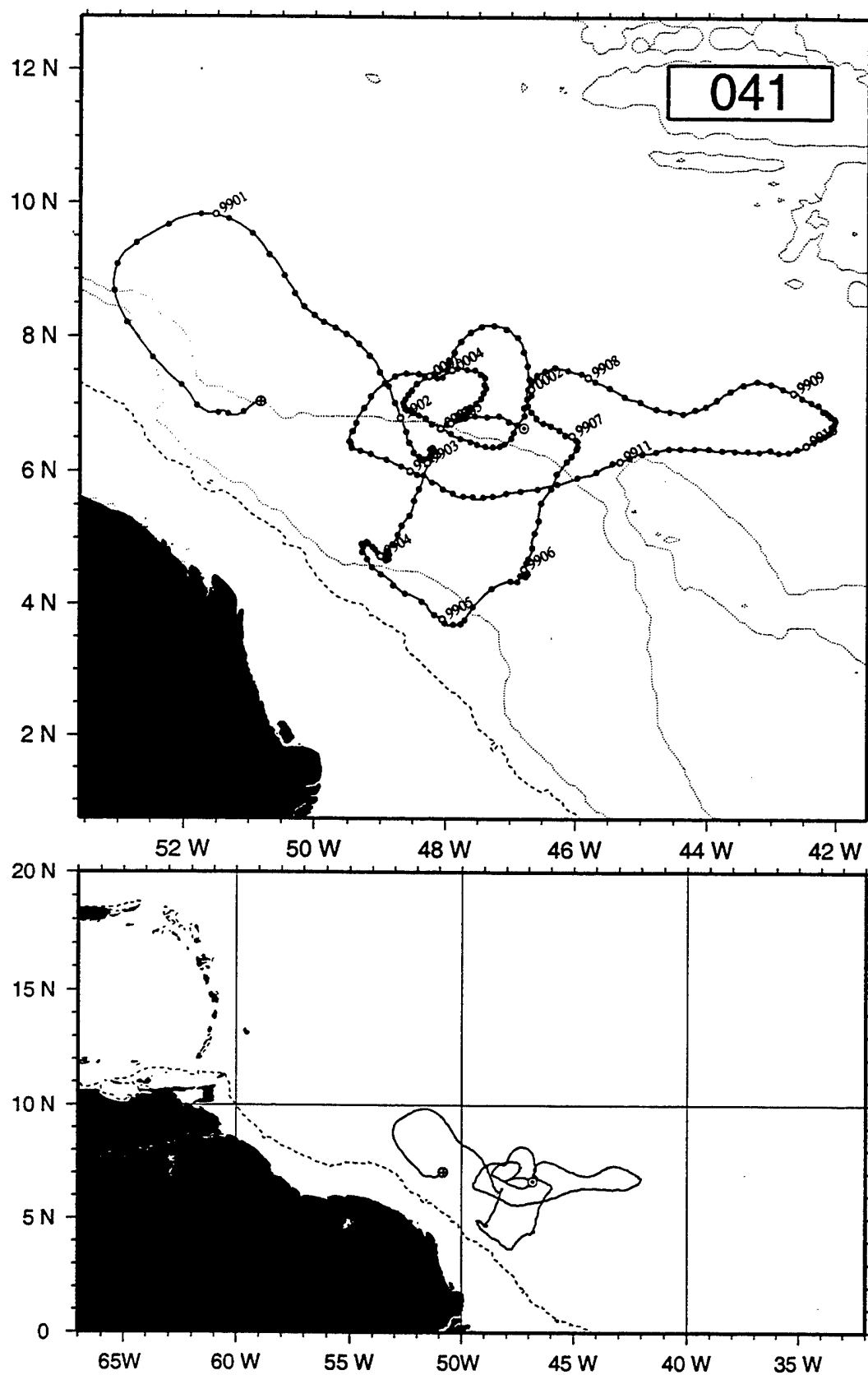




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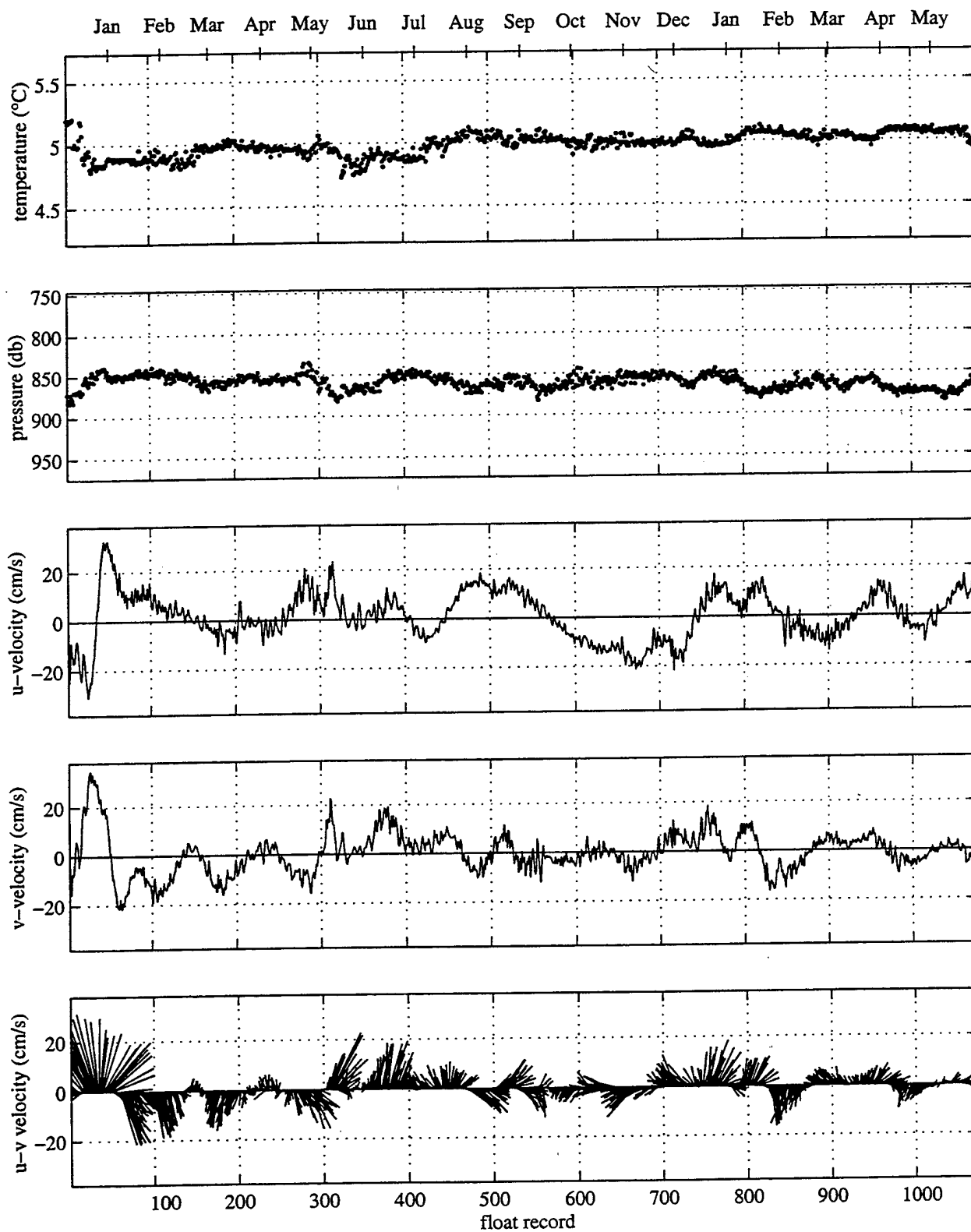


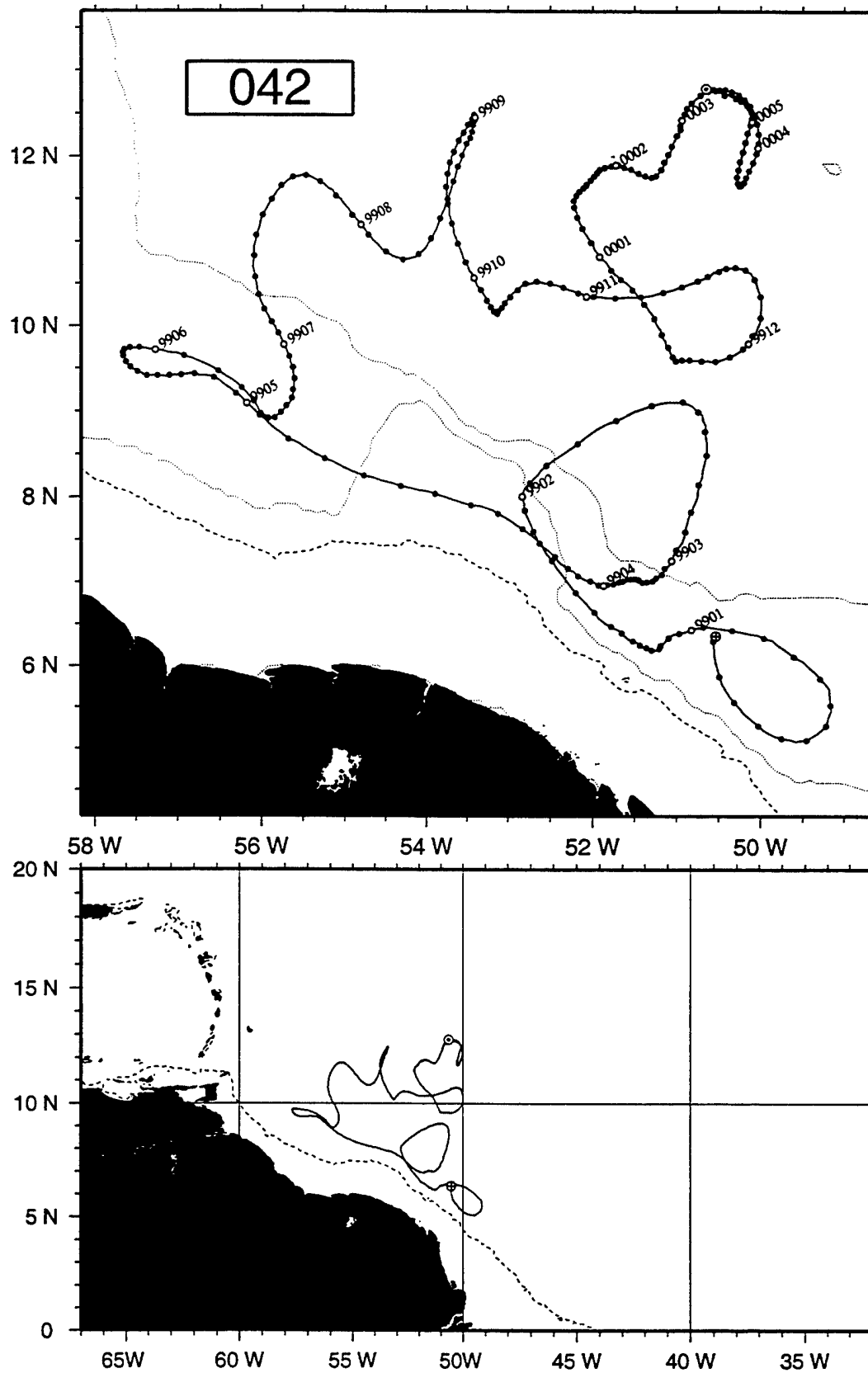


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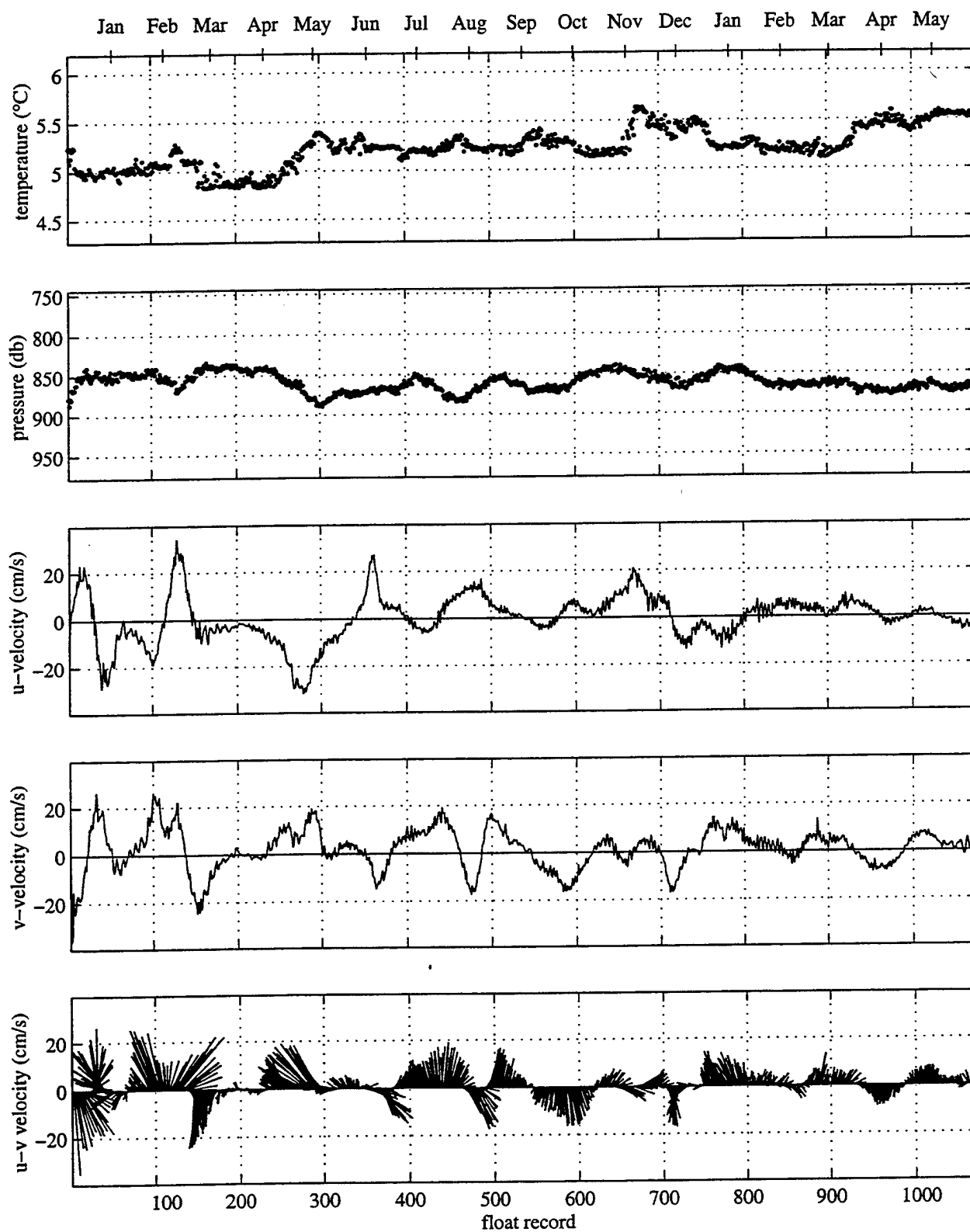


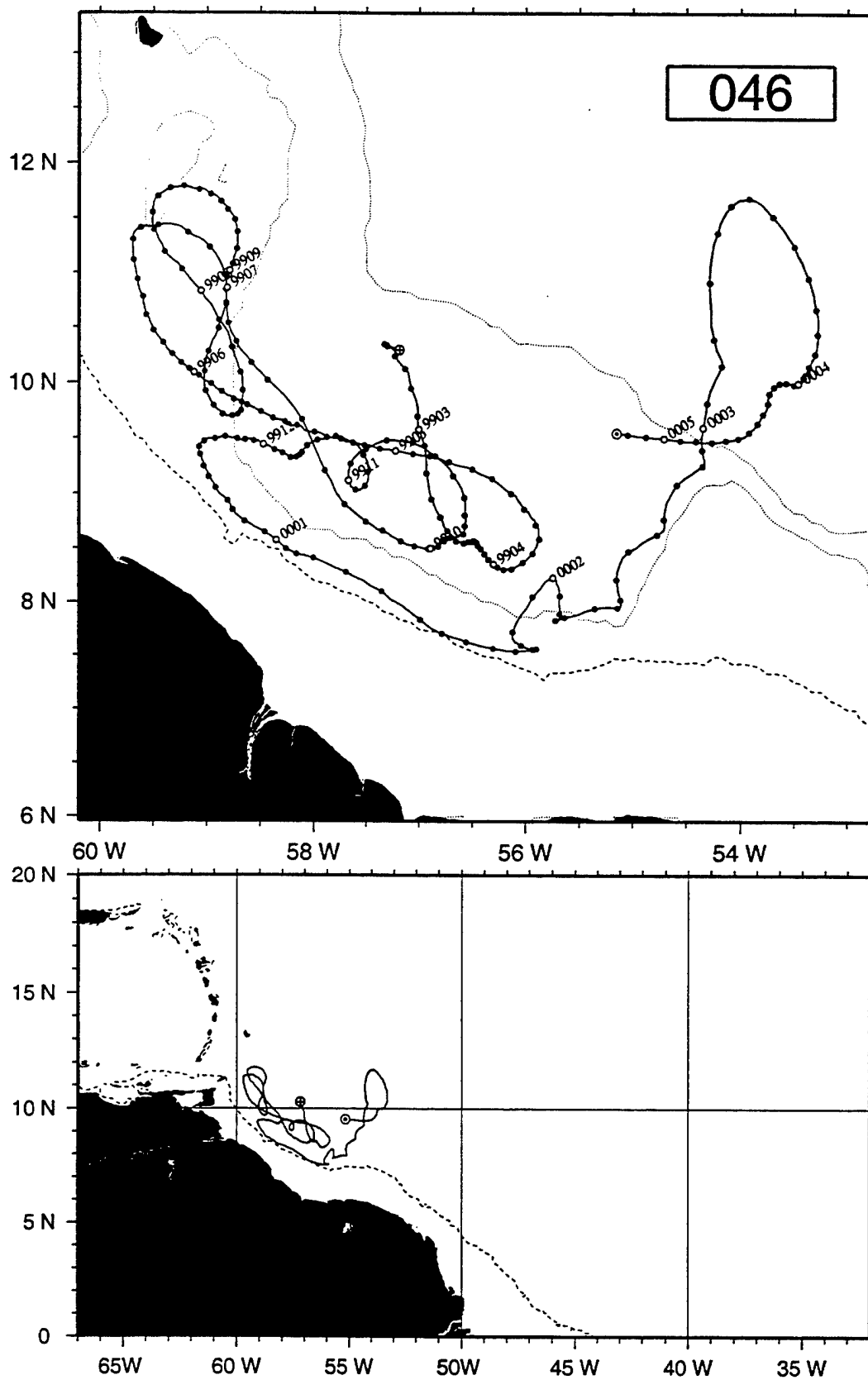


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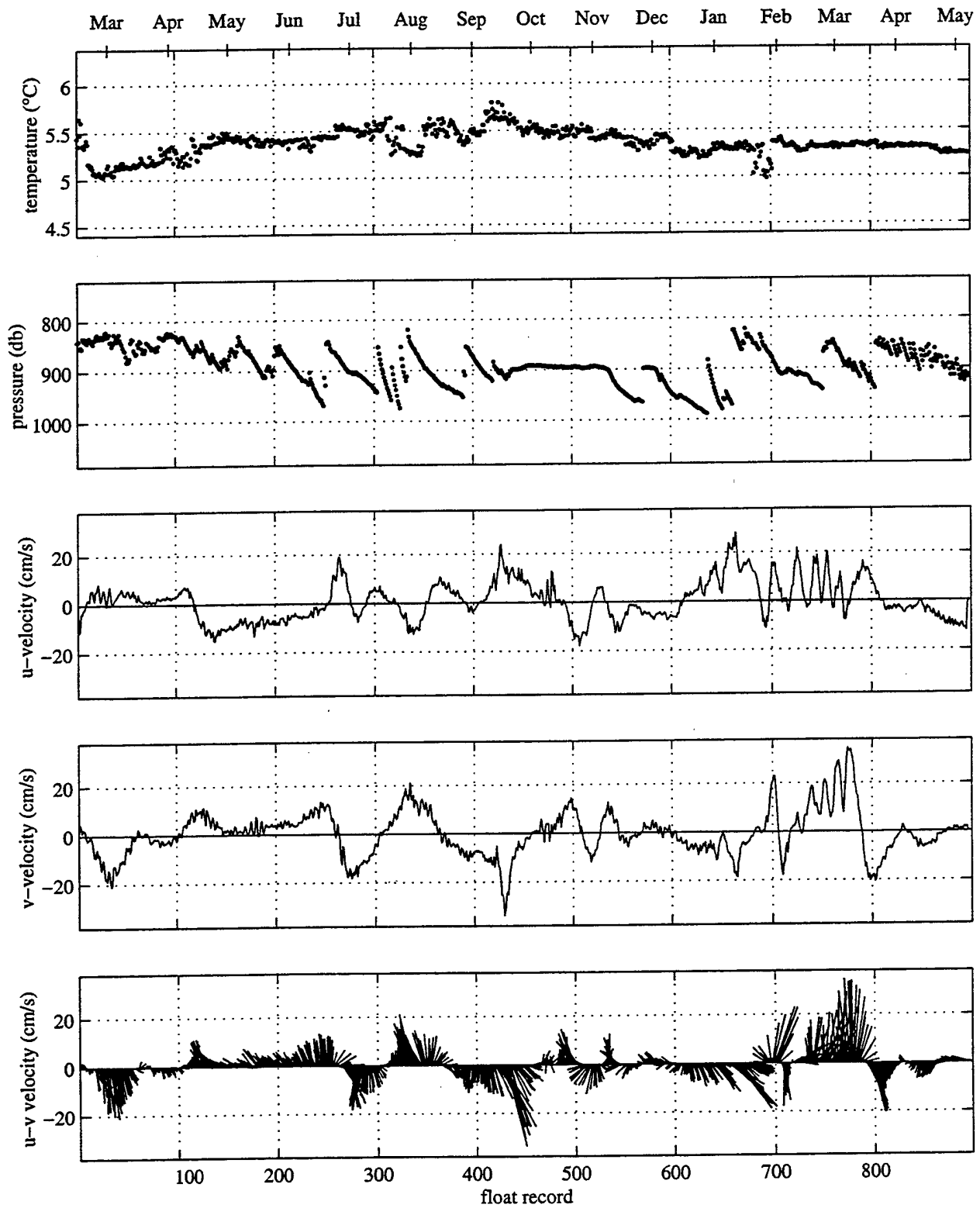


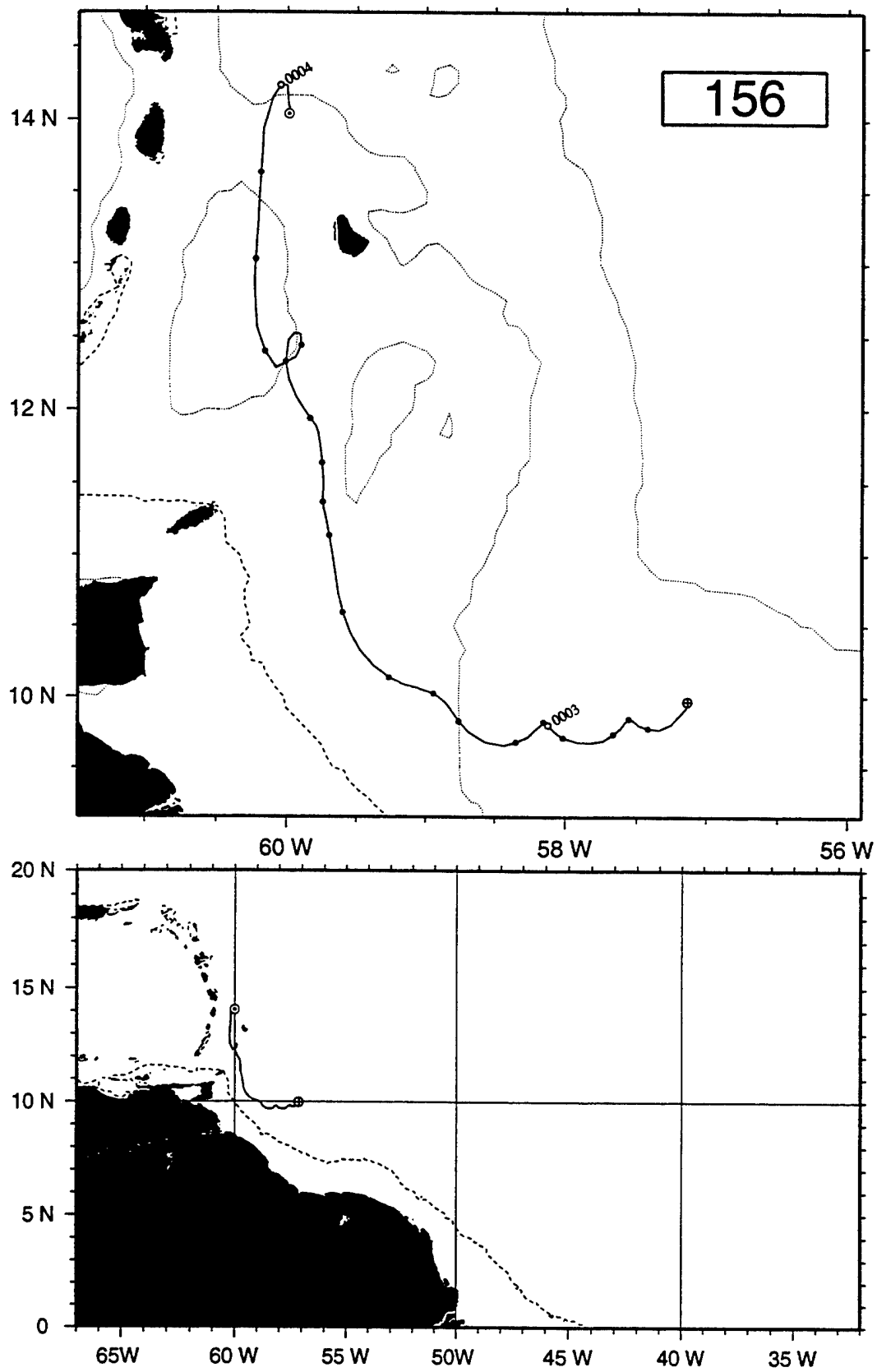




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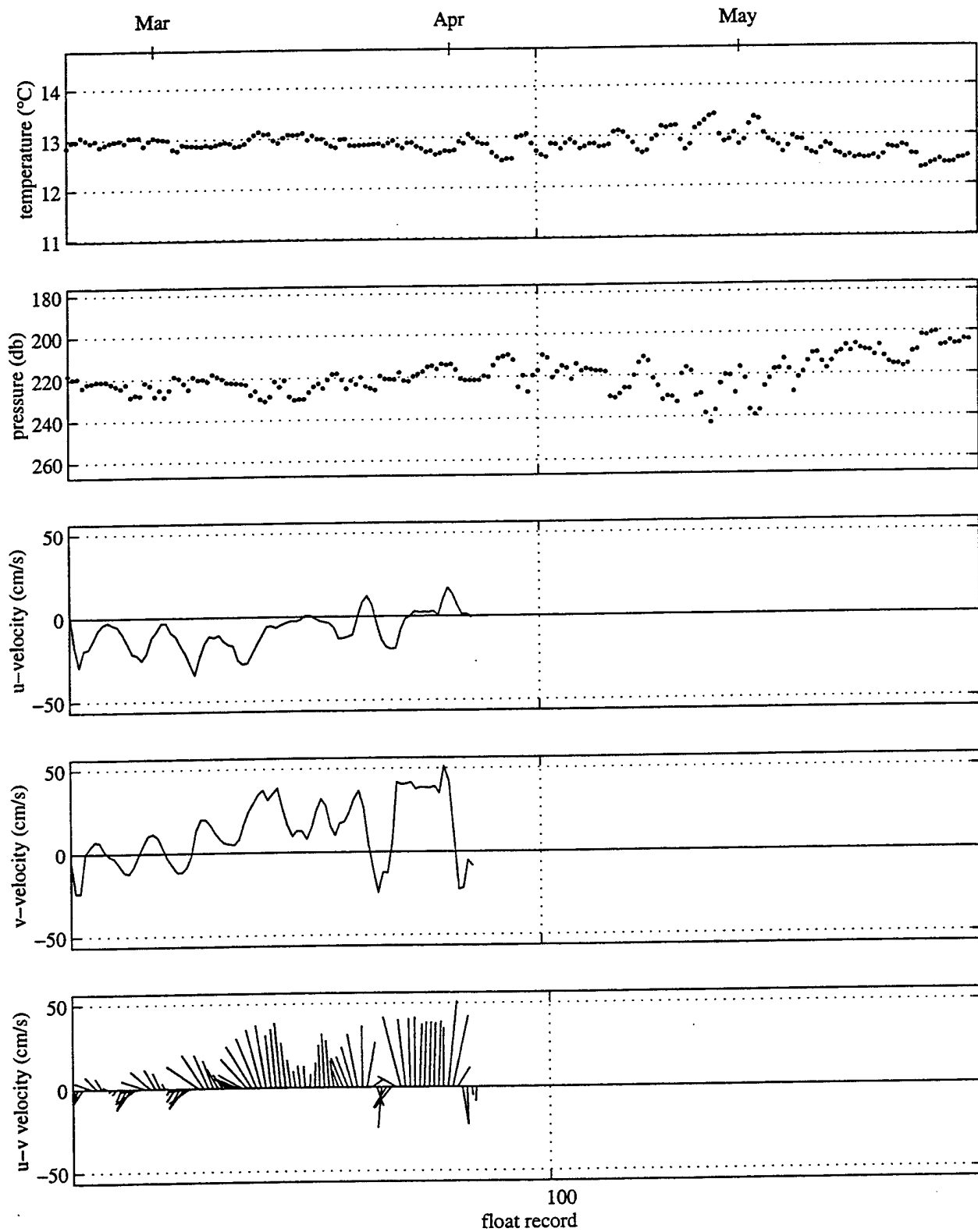
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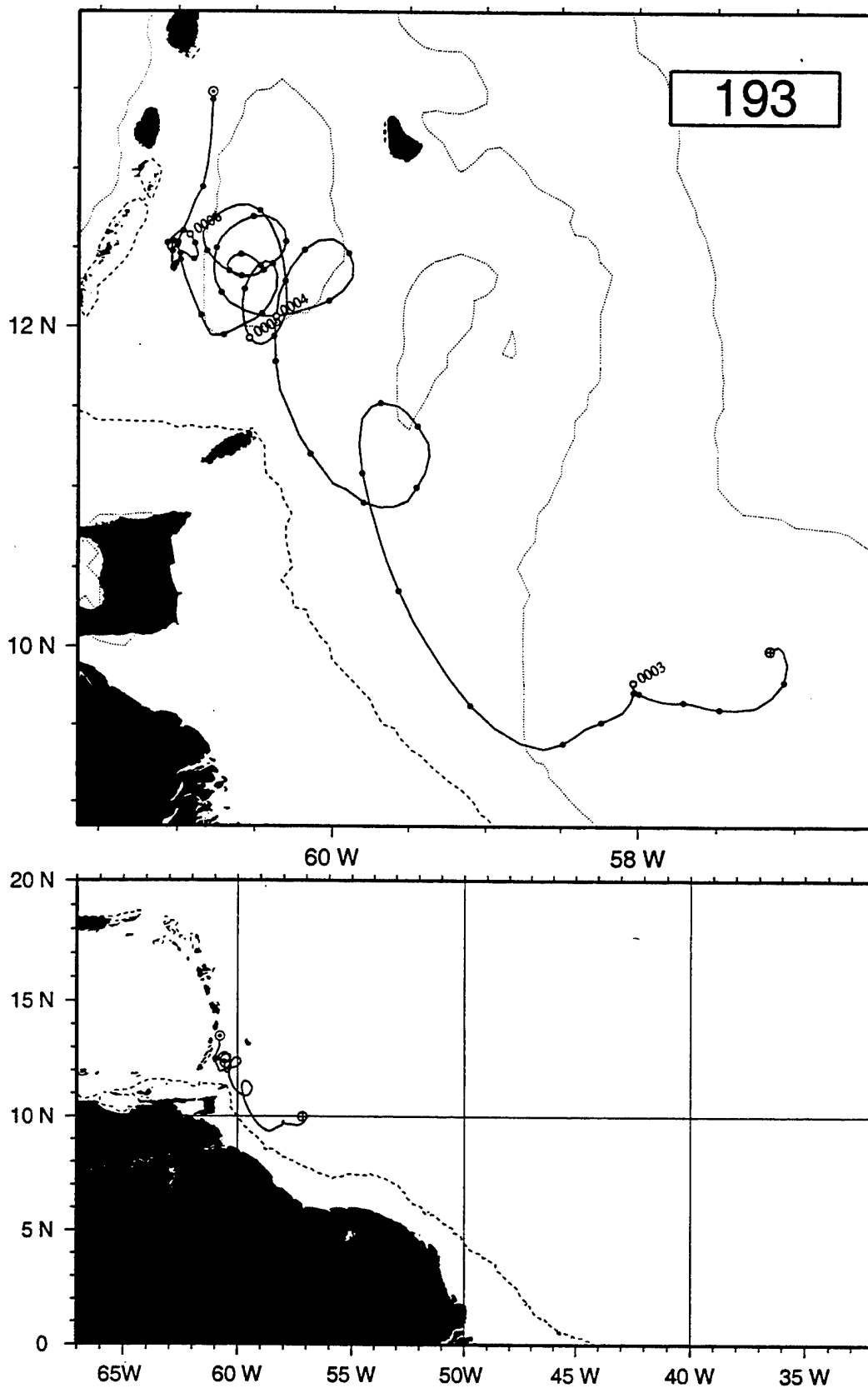




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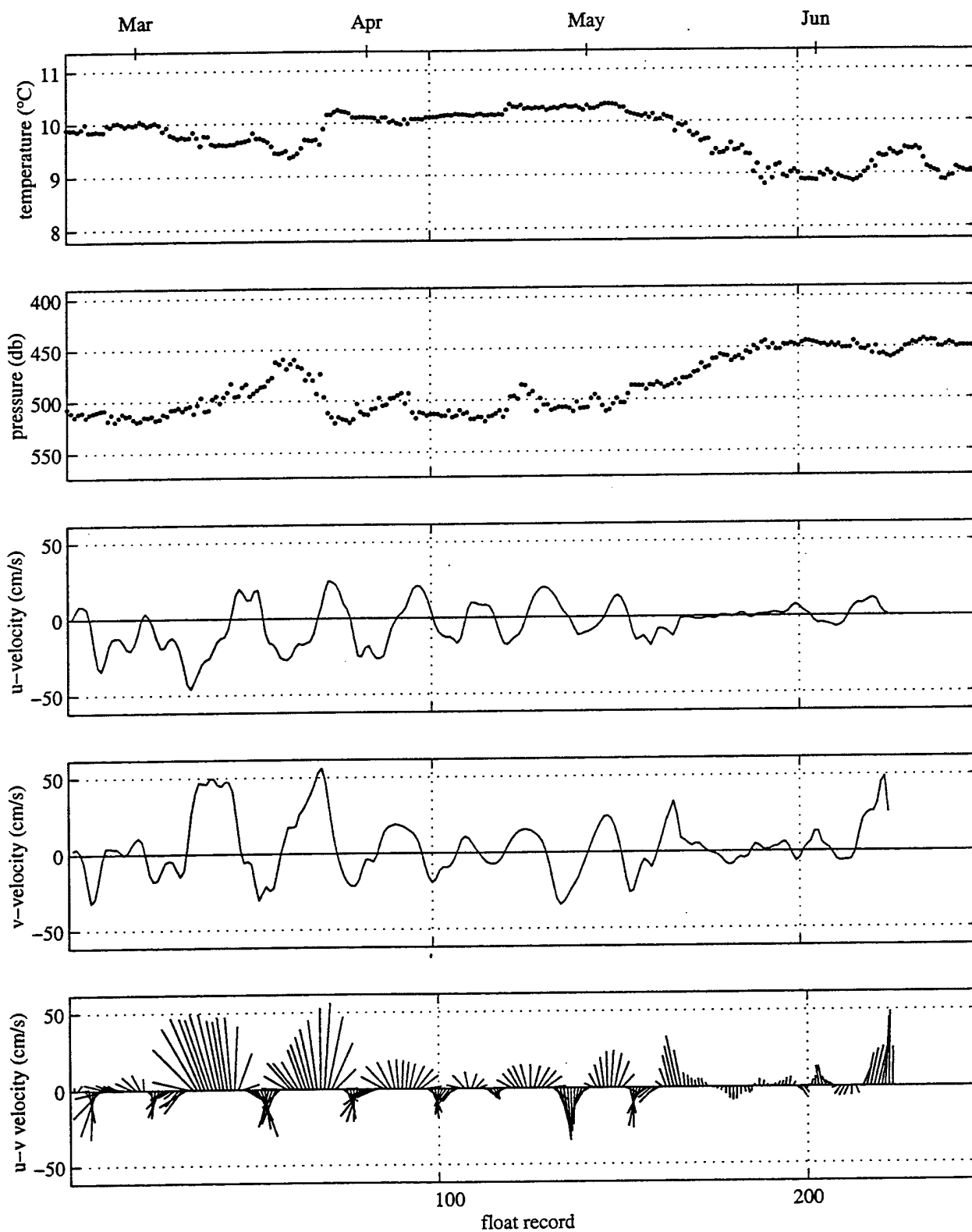
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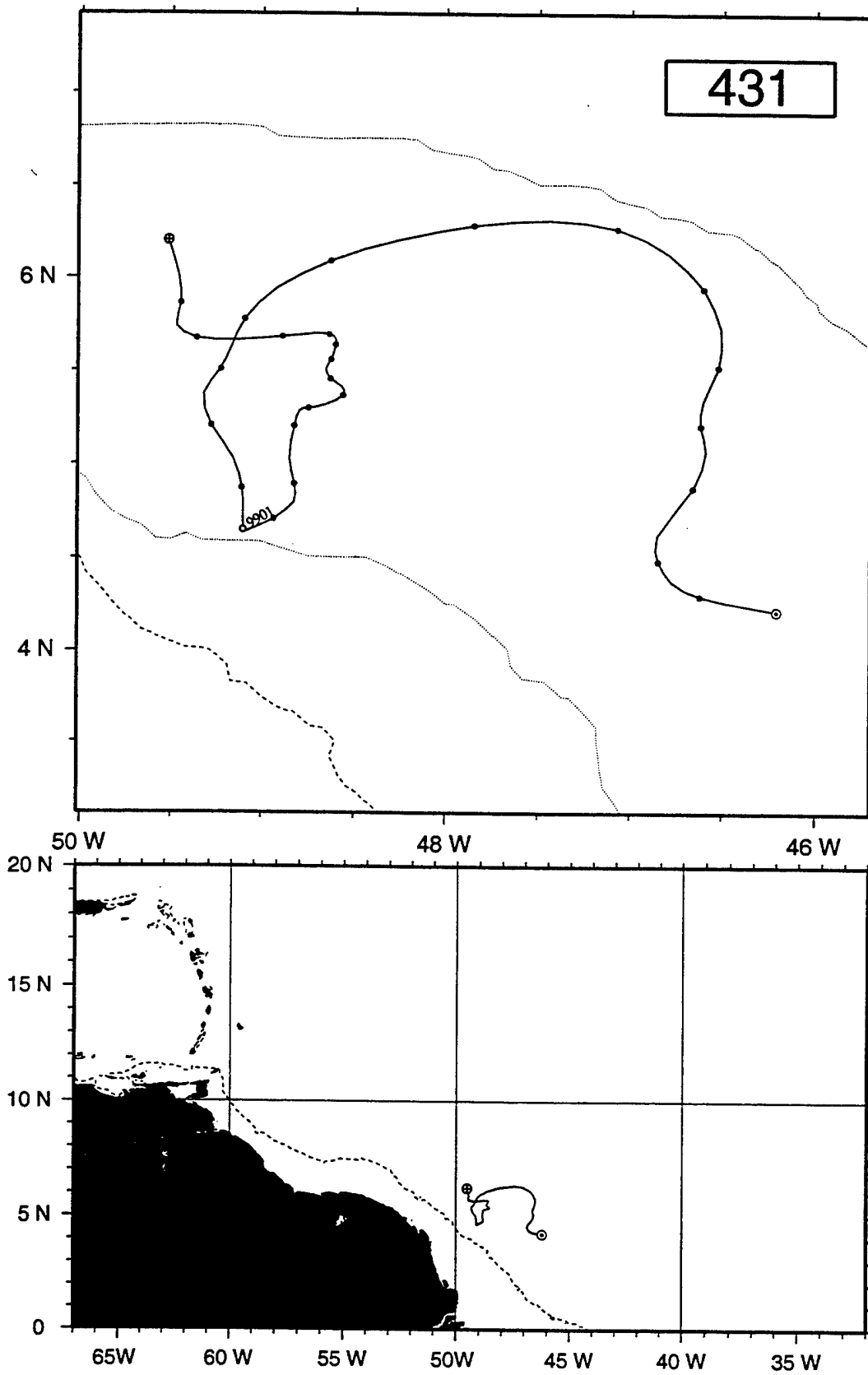




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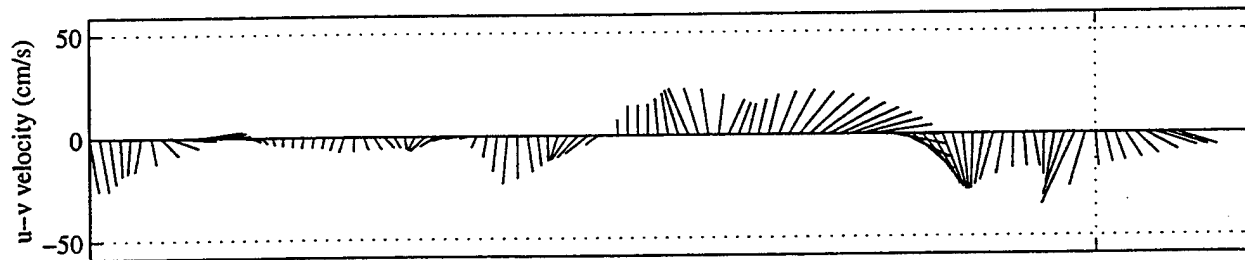
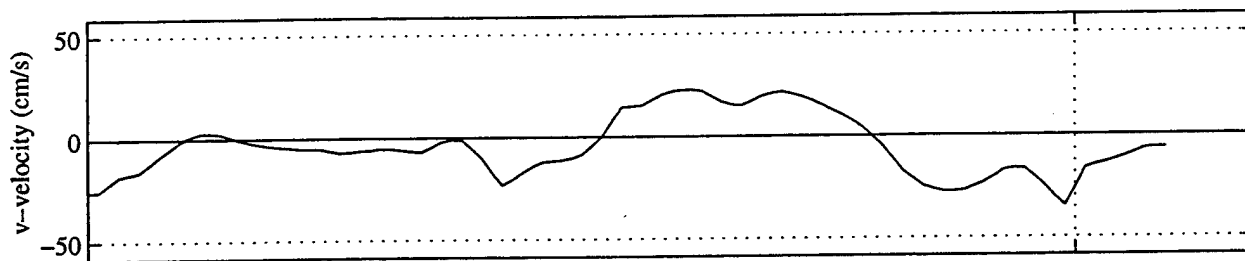
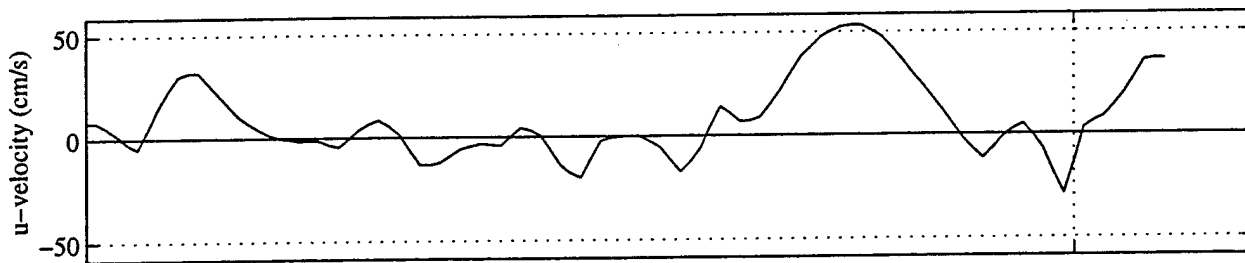
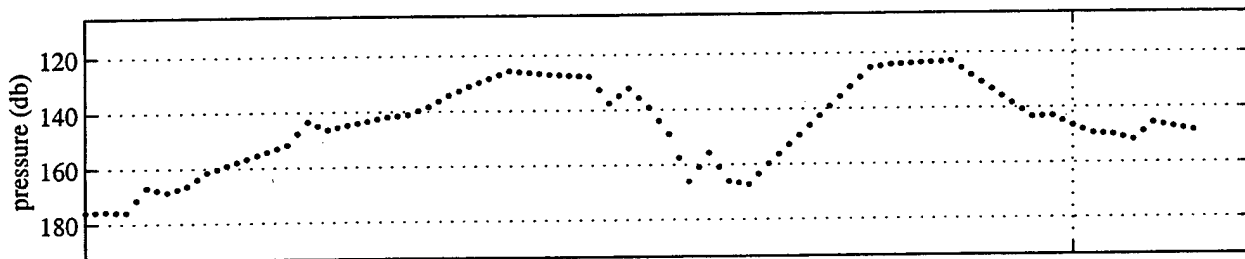
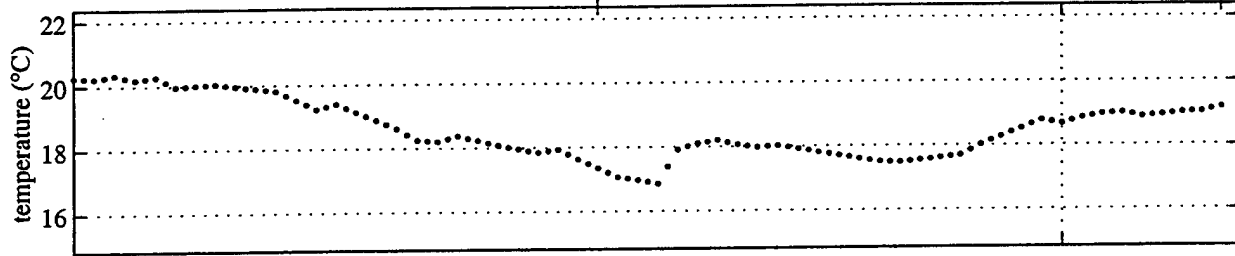


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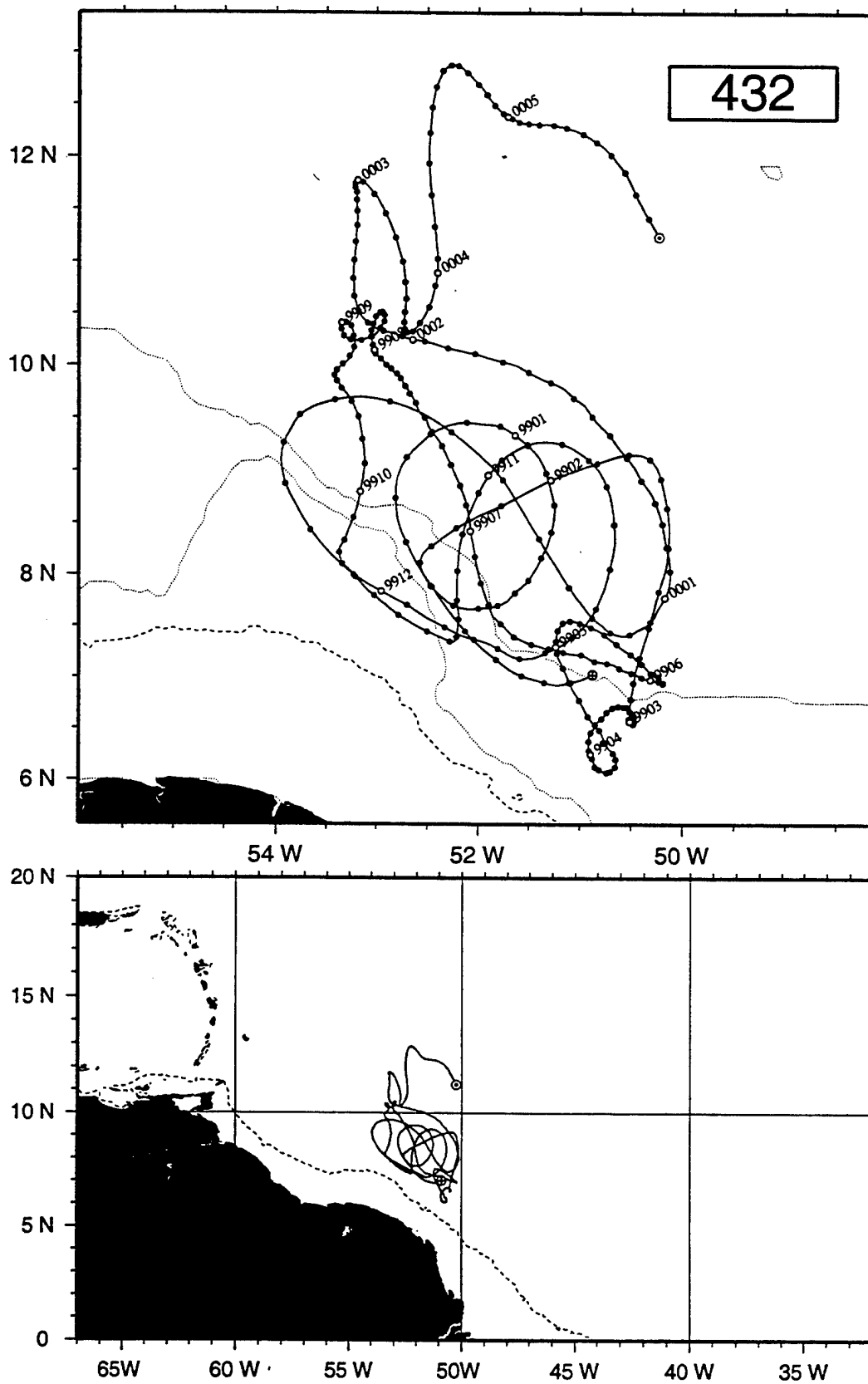
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float record

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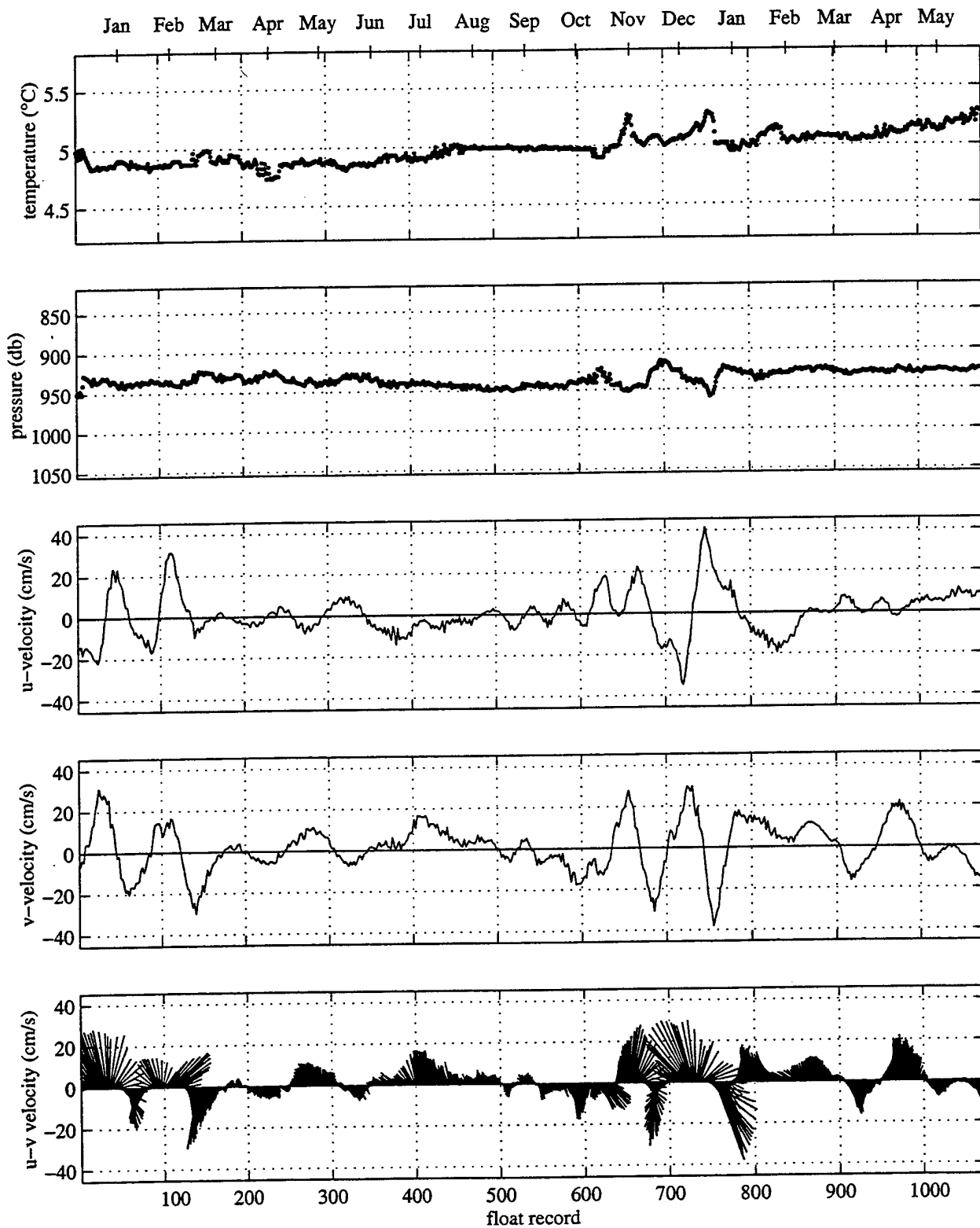


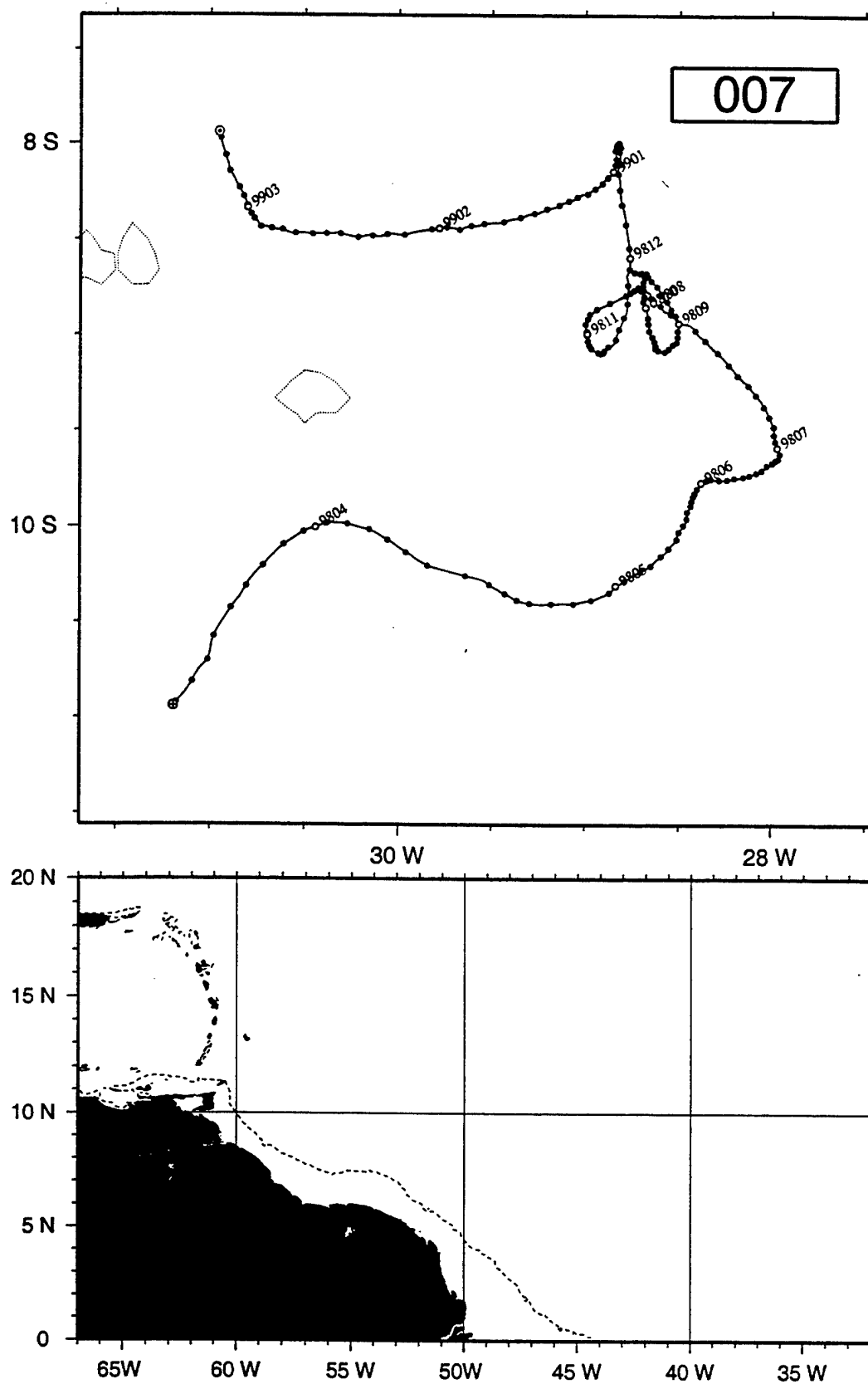


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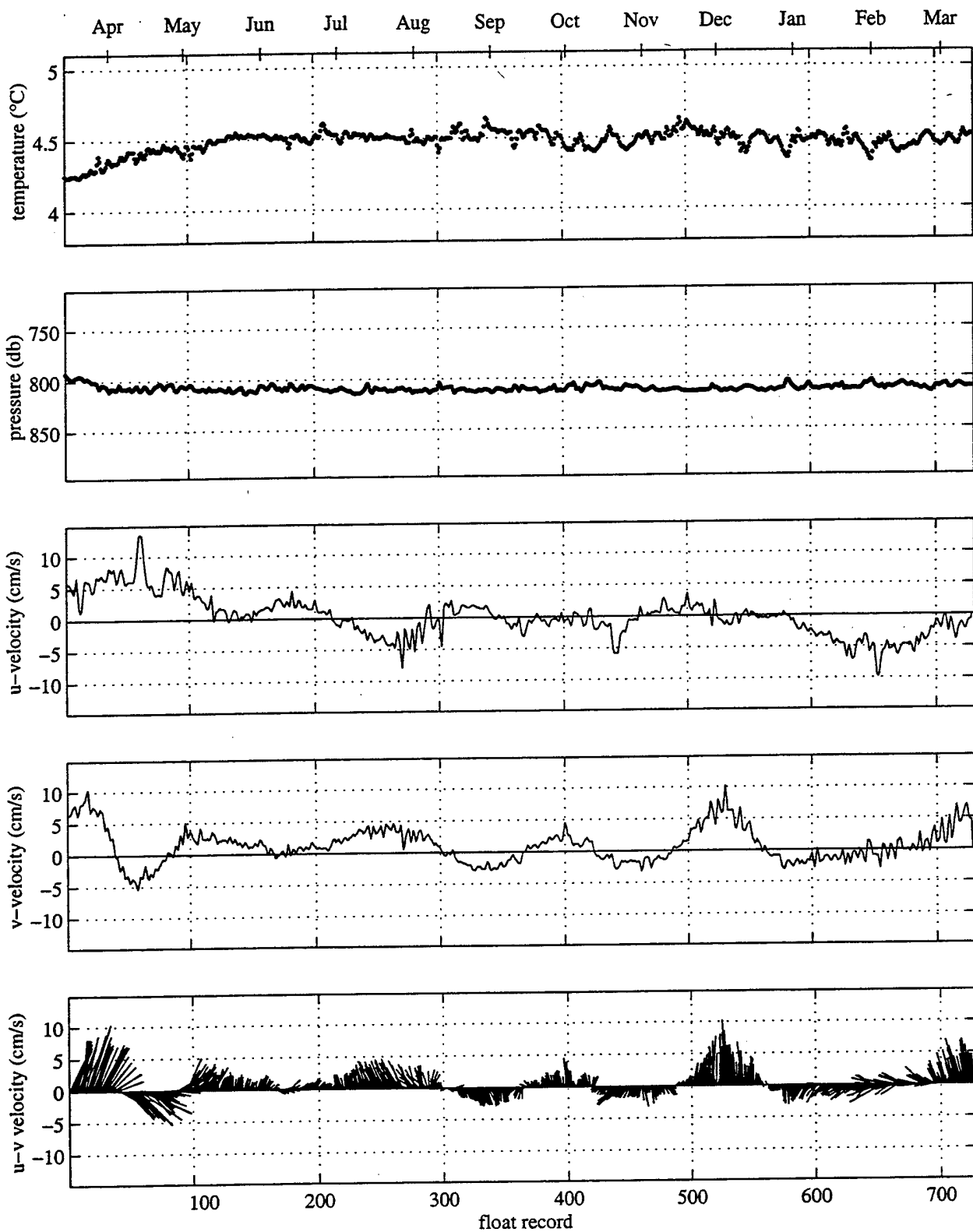
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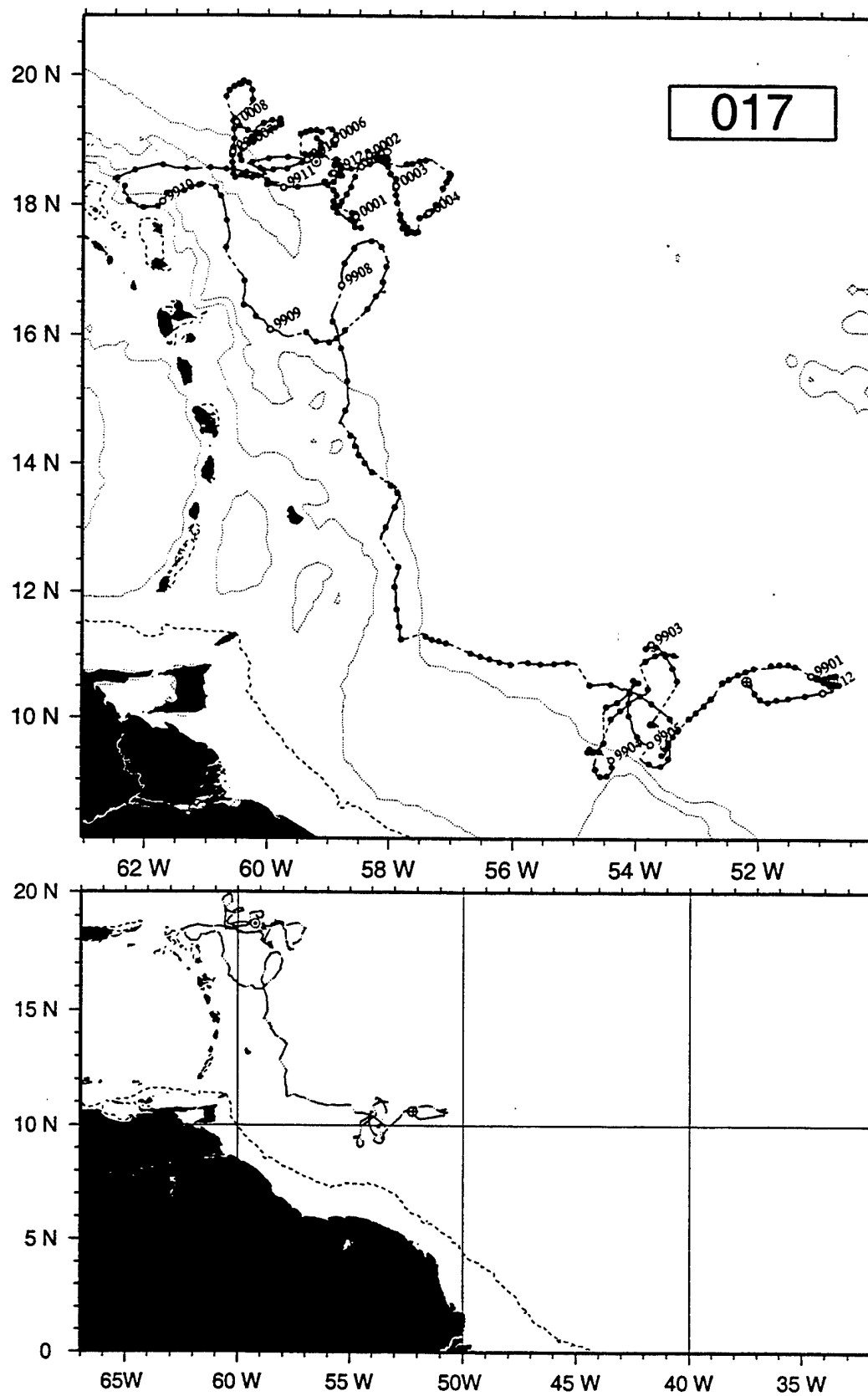




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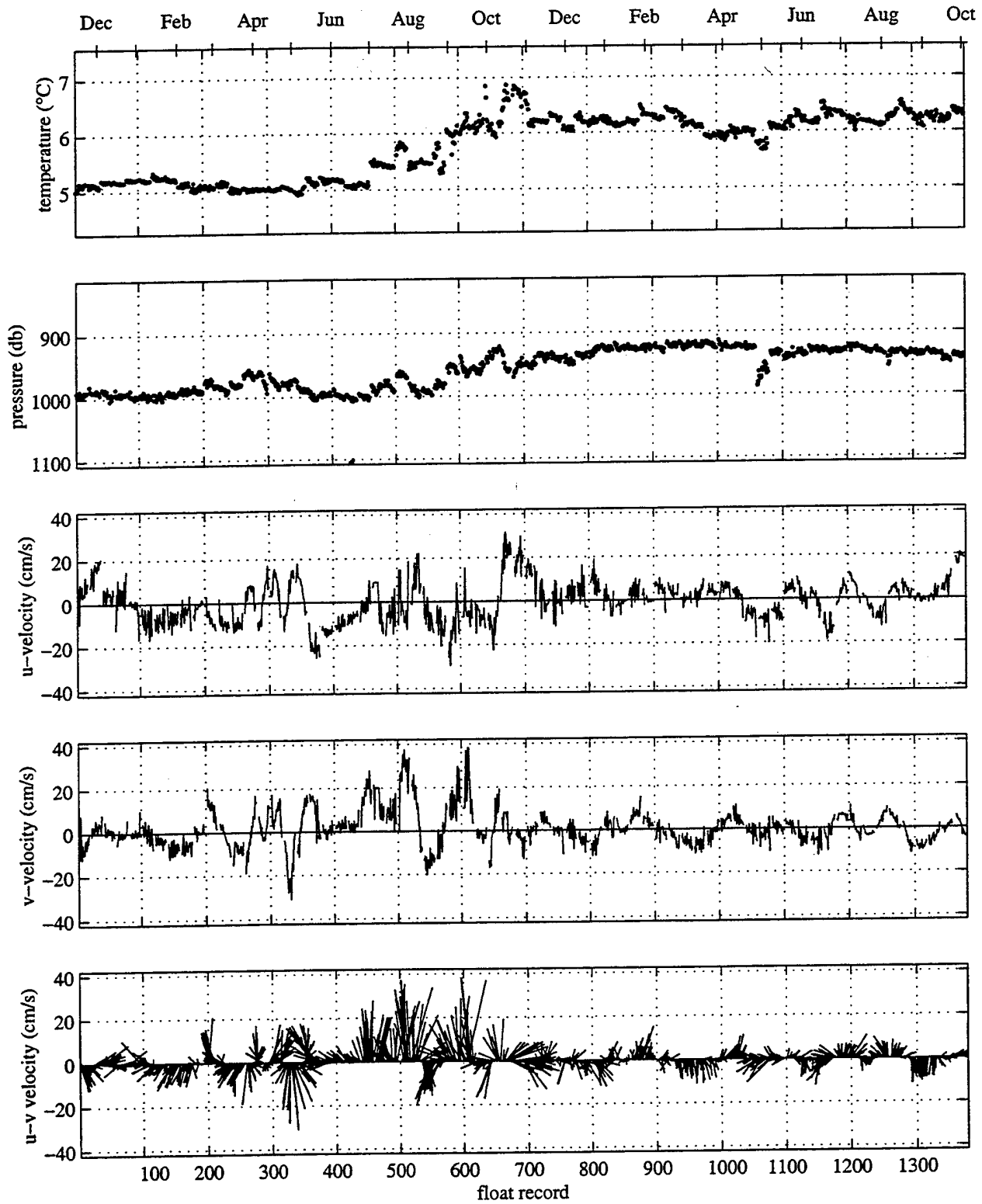




# br017

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